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THESIS

HEAT TRANSFER STUDIES OF A FLOW-THROUGH MODULE FOR ELECTRONICS COOLING

by

Erkan Yeniçeri

September 1995

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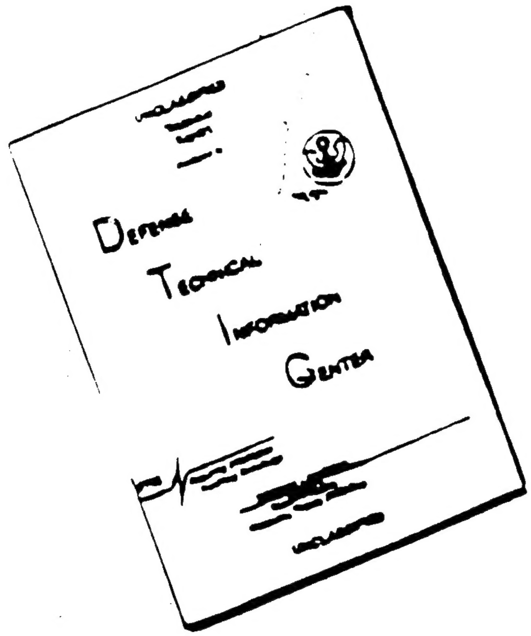

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HEAT TRANSFER STUDIES OF A FLOW-THROUGH MODULE FOR ELECTRONICS COOLING

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ABSTRACT

The thermal performance characteristics of an electronics cooling Liquid Flow Through Module (FTM) were experimentally investigated. Different sets of experiments were conducted for each side of the FTM. A synthetic dielectric polyalphaolefin type coolant, Brayco Micronic 889, was used. Six etched foil type heaters were attached to one side of the FTM over the fluid flow path while three heaters were attached to the other side of the module. Inlet and outlet fluid temperatures as well as surface temperature data were acquired from both sides of the module for several different flow rate and power setting combinations to quantify the effectiveness of the FTM. Correlations, in terms of Reynolds and Stanton numbers were formulated according to the data for both sides of the module.

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$\mathbf{I_h}$ (i) : Current Through Each Heater (Amp).

$\mathbf{I_p}$ (i) : Current Through Each Precision Resistor (Amp).

$\mathbf{V_p}$(i) : Voltage Drop Across Each Precision Resistor (Volt).

$\mathbf{R_p}$(i) : Resistance of Each Precision Resistor (Ohm).

$\mathbf{P_h}$ (i) : Power Supplied to Each Heater (W).

$\mathbf{P_T}$: Total Power Supplied to the Module (W).

$\mathbf{q_{fluid}}$: Heat Dissipated by the Coolant (W).

$\mathbf{q_{loss}}$: Heat Losses Through the Insulation (W).

Δq : Difference in Energy Balance (W).

ρ : Density of the Coolant (g / ml).

$\mathbf{c_p}$: Specific Heat of the Coolant (J / g °C).

ν : Kinematic Viscosity of the Coolant (m^2 / s).

$\dot{\mathbf{Q}}$: Flow Rate of the Coolant (ml / min).

$\mathbf{T_{avg}}$: Average of Coolant Inlet and Outlet Temperatures the Coolant.

$\bar{\mathbf{T}}_{diff}$: Average of Differential Temperature of the Coolant Between Inlet and Outlet (°C).

$\bar{\mathbf{T}}_{surf}$: Average Module Surface Temperature (°C).

ΔT_{LM} : Log Mean Temperature Difference (° C)

k : Thermal Conductivity of the Insulation (W / m °C).

A : Surface Area of the Insulation (m^2).

L : Thickness of the Insulation (m).

$\mathbf{A_{eff}}$: Effective Heater Area (m^2).

q'' : Heat Flux (W / cm^2).

i : Index for Heaters and Precision Resistors from 0 to 8.

Re : Reynolds Number.

St : Stanton Number.

$\mathbf{D_h}$: Hydraulic Diameter (m).

$\mathbf{A_c}$: Cross-sectional Area of a Single Channel (m^2).

P : Perimeter of a Single Channel (m).

h : Height of a Channel (m).

b : Width of a Channel (m).

B : Width of a Passage (m).

$\mathbf{A_f}$: Free Flow Area (m^2).

$\mathbf{U_m}$: Mean Velocity of the Coolant Through the Channels (m/s).

$\frac{\delta f}{f}$: Uncertainty in Function " f " (%).

$\frac{\delta x}{x}$: Uncertainty in Variable " x " (%).

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I. INTRODUCTION

A. OVERVIEW

Since the development of the first integrated circuits (IC), there has been a steady increase in heat dissipation levels of electronic devices. This increase has made the role of heat transfer and thermal design more important than ever. The necessity for advanced techniques in electronic cooling started with large-scale integration (LSI) technologies of the 1970's in which 1000 junctions per chip were achieved. This continued with very large-scale integration (VLSI) technologies of the 1980's in which 100,000 junctions per chip were achieved [5]. The magnitude of this thermal stress problem becomes more apparent when microelectronics trends are examined. Microprocessor clock frequencies have been doubling every five years and as clock speeds increased, almost linearly, so did heat dissipation levels. Today's technology has achieved 75-100 MHz system clock speed or even higher. Therefore 400-500 MHz clock speed could be expected towards the end of this century. Thus a 500 MHz electronic device will dissipate 5 times the heat dissipated at 100 MHz [10].

These trends indicate that thermal stress management will always become a major problem in electronic packaging. Higher thermal stresses will result higher failure rates, shorter operational lifetimes and higher logistics and maintenance costs.

There are several advanced thermal control techniques to improve cooling efficiency. Since the improvements in reliability and packaging density of electronic devices are directly related to advances in thermal design, the choice of thermal control technology has large effects on reliability and cost. Insufficient attention to thermal control may easily result in device failure. On the other hand thermal overdesign may result very high product costs. By taking care of these two criteria: reliability and cost,

many new thermal control techniques involving liquid cooling, have been proposed. These new liquid cooling techniques can be grouped as follows:

a. Jet Impingement and Nucleate Boiling Cooling

b. Microchannel Cooling

These techniques will be discussed briefly in the following sections.

B. AIMS OF THERMAL CONTROL

The primary aim of thermal control is to prevent catastrophic failure which can be defined as immediate, thermally induced, total loss of electronic function. Catastrophic failure may result from melting or even vaporization of a component in microelectronic devices and in particular may also result from plastic flow of printed circuits.

Catastrophic failure is generally dependent upon the local temperature field as well as the operating history. Therefore it is difficult to precisely determine where such failure can be expected to occur. However, maximum allowable temperatures can be found in manufacturer's catalogs by which the possible range of component variations can be taken into account. Likewise, the possible range of environmental variations is another prerequisite for developing designs of thermal control systems [5].

C. ADVANCED LIQUID COOLING TECHNIQUES

Natural Convection and radiation cooling, relying upon the ambient air, is insufficient to deal with the rapidly increasing heat fluxes. Figure -1 shows the relationship of the tremendous increase in Microelectronics heat fluxes to other technologies [5].

On the other hand, conventional forced convection air cooling can no longer satisfy heat removal requirements. As shown in Figure -2 , at lower air velocities, typical heat flux limits, for packages cooled by conventional forced convection, are less than 1 W/cm^2 [12].

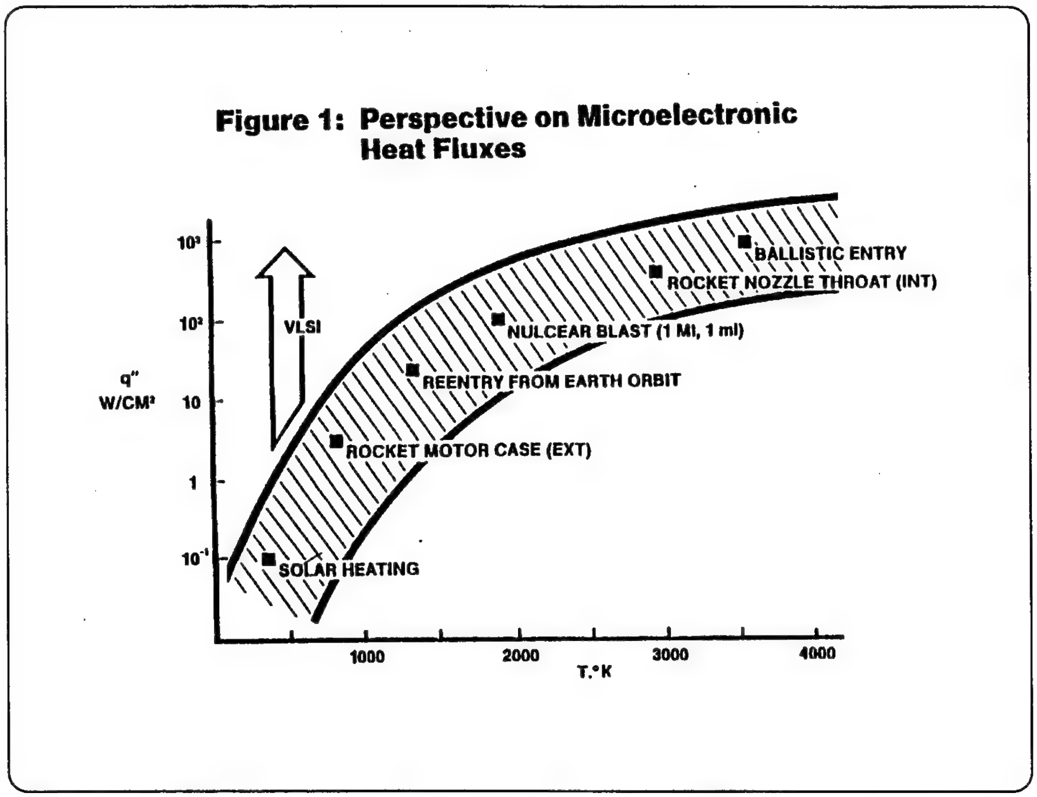


Figure 1. Perspective of Increase in Microelectronic Heat Fluxes [5].

In the near future, technology will be able to produce very-large scale integrated (VLSI) chips dissipating up to 200 W/cm^2 [7]. To achieve a board level heat flux that can be cooled with conventional forced convection, package surface area must exceed total chip surface area by more than 25 times. For example, a forced convection cooled package containing 10 chips having 1 cm^2 area each, would require 250 cm^2 of surface area. Therefore it is obvious that conventional forced convection will not be applicable for today's VLSI electronic systems. However conventional air cooling is an important milestone which leads to the development of alternative methods of cooling. Temperature differences attainable as a function of heat flux for various heat transfer modes, and various coolant fluids is shown in Figure -3 [5].

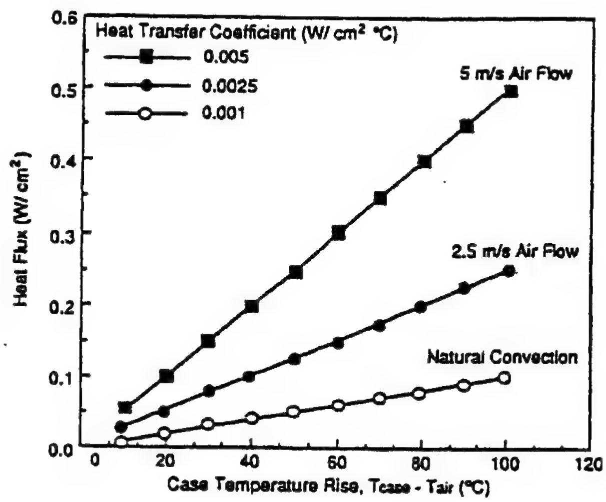


Figure 2. Package Heat Flux in Air Cooled Packages [12].

1. Jet Impingement and Nucleate Boiling Cooling

Alternative approaches to achieving high heat flux removal are to apply liquid - jet impingement, with or without boiling, or direct immersion cooling, so called "pool boiling", to the backside of silicon chips. Convective heat transfer associated with gas jets has been a research topic since the mid- 1950s, but jet impingement cooling with dielectric liquids is a recent improvement. In this cooling method there are two modes. Liquid may flow to the heater through a vapor / gas space or through a liquid - filled space. The first is called a "free-jet", and the latter is called a "submerged jet" [11]. High convective heat transfer coefficients can be achieved in this latter cooling mode. Thus "submerged jet" impingement cooling is one of the best alternatives in direct liquid cooling of electronic components.

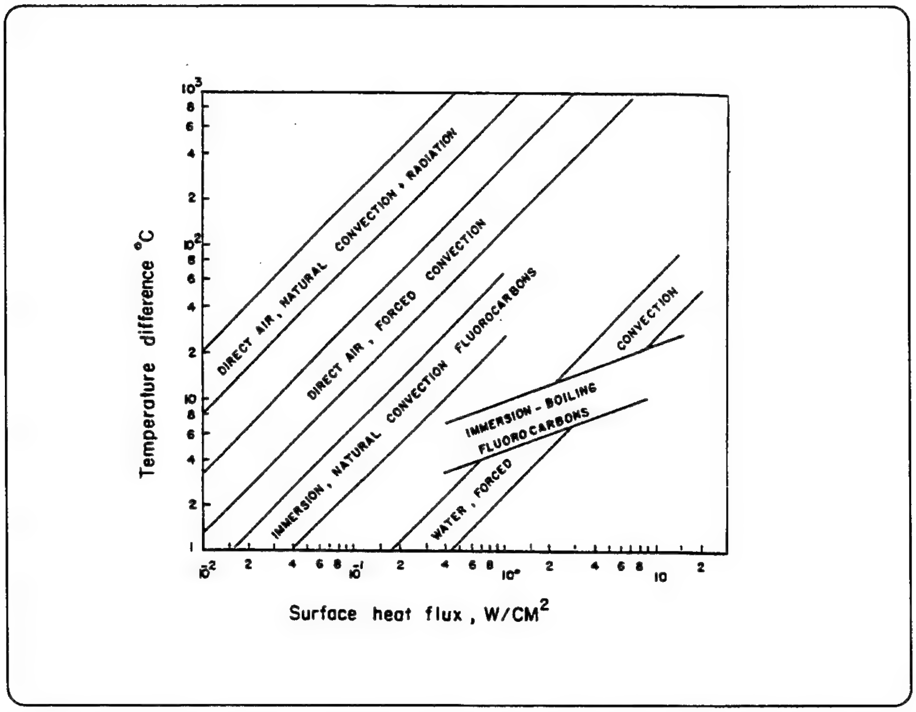


Figure 3. Temperature Differences Attainable as a Function of Heat Flux for Various Heat Transfer Modes and Various Coolant Fluids [5].

2. Microchannel Cooling

One of the best known cooling methods is the microchannel approach. In this technique, heat fluxes approaching 800 W/ cm^2 with a temperature rise of 70°C have been achieved by using water as the working fluid [12]. These microchannels mentioned here, can be formed by *plain fins, wavy fins, pin fins* or *offset strip fins*. Offset strip fin type is the one which is widely used in microchannel designs.

In this study, a Standard Electronic Module (SEM) which is manufactured by Lockhart Industries, has been investigated. Also in this Flow Through Module (FTM), which is a format- E size, offset strip fins have been used to increase the heat transfer coefficient by interrupting the flow so that the fluid boundary layer can never become too thick to reduce convective heat transfer. The flow is also more uniform than straight fins since it is a developing laminar flow through the microchannels formed by offset strip fins [8]. Typical rectangular offset plate fin exchanger and general notations of offset plate fins are shown in Figure - 4 [7].

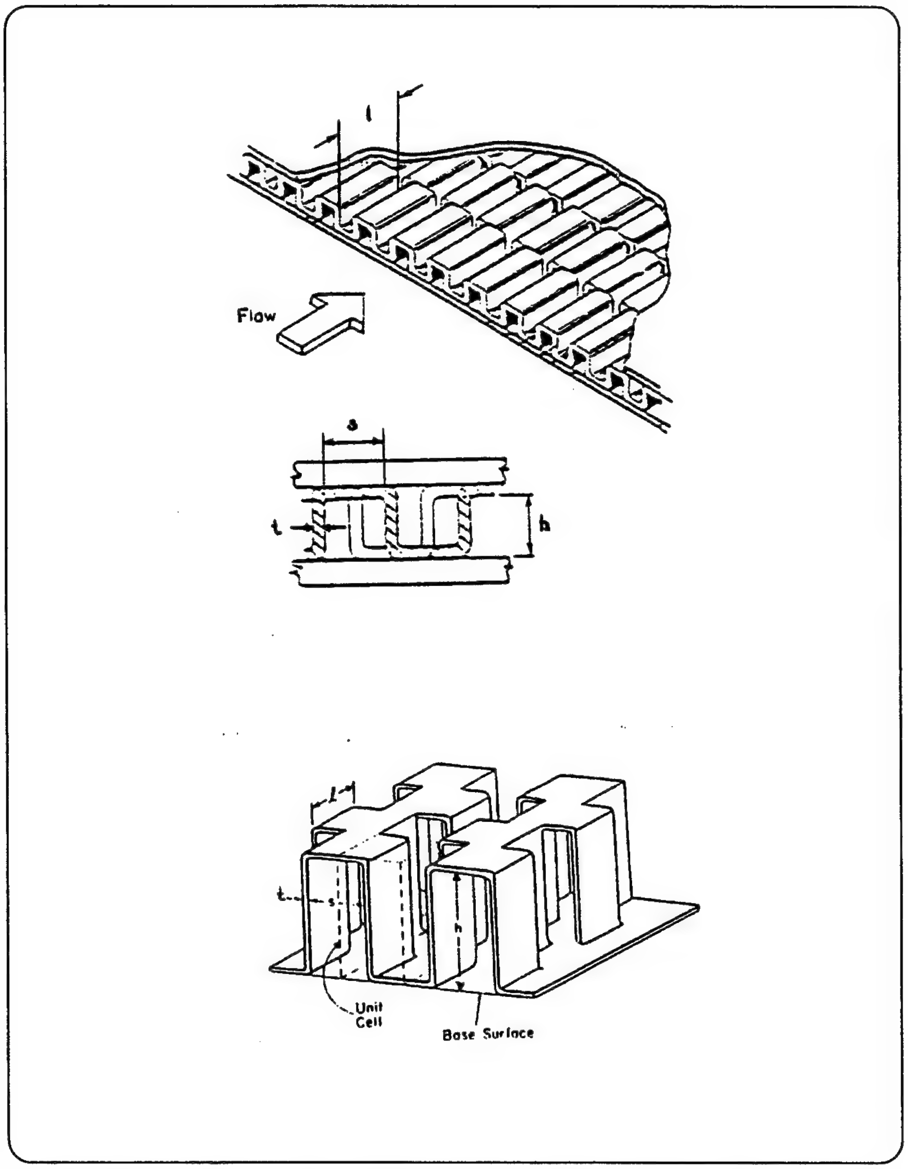


Figure 4. Typical Rectangular Offset Plate Fin Heat Exchanger and General Notation Used for the Dimensions of an Offset Plate Fin [7].

Many experimental investigations have been conducted to improve the convective heat transfer coefficients by using fins. These studies dealt mostly with gases. Therefore the usefulness of these data is very limited when applied to liquid coolants, because Prandtl number which is a fluid property, has a significant effect on heat transfer coefficient. These tests have been conducted by Lockhart, for different fin pitches and fin heights, for Reynolds numbers varying between 30 to 2700 and Prandtl numbers from 0.7

to 70. The test results indicated that the Colburn j and the flow friction factors, are different for selected types of fluids within the same Reynolds number range [8]. Therefore Kays' and London's air test data, [9] is not applicable to fluids which are outside the gas Prandtl number range, since the test results obtained by Lockhart confirm the Prandtl number effects.

On the other hand there may be some disadvantages associated with liquid cooling, such as additional assembly relating to coolant circulation and refrigeration systems. Also the possibility of leakage may cause damage to the electronic components. That is why dielectric coolants are used in liquid cooling systems for electronics. In this study Brayco Micronic 889, manufactured by Castrol, has been used. This liquid is a polyalphaolefin (PAO) made for use in closed loop systems. Properties of Brayco Micronic 889 are given in Appendix-C.

3. Liquid Flow-Through Modules

In this study the effectiveness of a liquid Flow-Through Module (FTM) manufactured by Lockhart Industries, using PAO, is investigated. Flow-Through modules are manufactured by a technique so called "vacuum brazing" which facilitates the construction of microchannels in a very thin module. The module tested, shown in Figure-5, has a thickness of 0.100 inch , with 0.020 inch Aluminum 6061 faceplates.

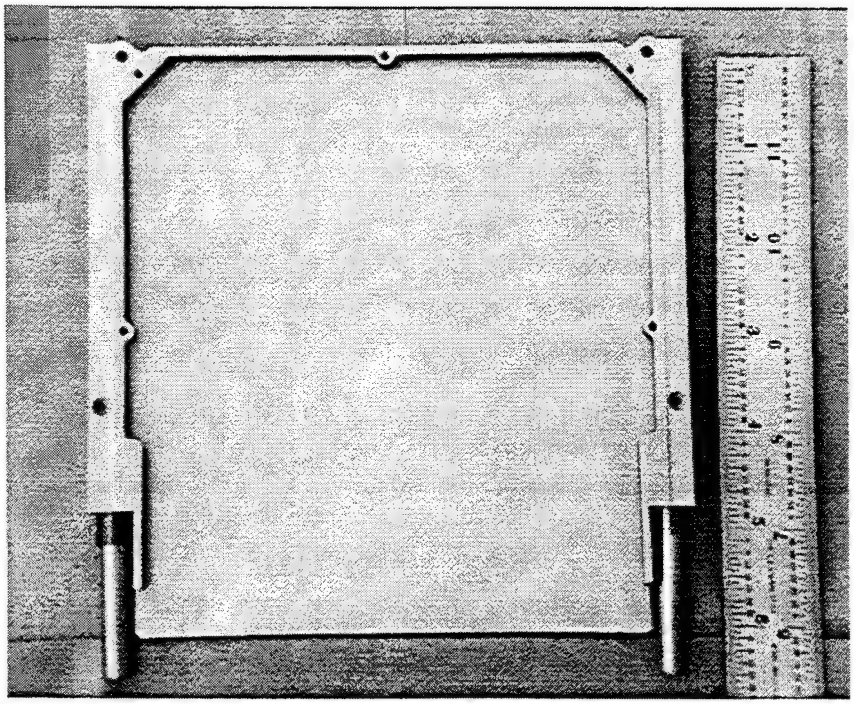
The fins within the module are made from an alloy, Aluminum 3003 and have 0.06 inch height, 0.125 inch length and 0.006 inch thickness. The fin density is twenty fins per inch. [2] A schematic drawing of the fins is shown in Figure -6.

Both sides of the FTM, shown in Figure -5, can be used for cooling electronic components. Electronic components placed on the surface of the FTM are cooled by the coolant flowing through the module. The thin structure of the module is very helpful for stacking purposes. Several modules can be housed in a small enclosure. For example, in a study performed by AT&T Bell Laboratories about Liquid Flow-Through cooling for avionics applications, 52 FTM's have been housed in a small enclosure. Both the module

and the system have demonstrated very high cooling efficiency and good reliability under shock and vibration testing [10]. The FTM tested in this study, shown in Figure 7, consists of three main flow paths of microchannels formed by offset strip fins. The flow pattern of the coolant is shown in Figure -7 [2]. The FTM is currently under evaluation by the military for naval and avionics applications [1].

D. OBJECTIVES

This study experimentally investigated the capacity for heat removal of the SEM-E sized Flow-Through Module, using a synthetic dielectric polyalphaolefin coolant, so called Brayco Micronic 889 , manufactured by Castrol. Experimental investigation was conducted for both sides of the FTM by utilizing several different flow rate and power setting combinations. Temperature data were collected from both sides of the FTM in order to quantify the effectiveness of the module. Correlations, in terms of Reynolds and Stanton numbers were formulated. According to the temperature data collected from the module inlet and outlet, heat dissipation capabilities of the FTM were quantified.



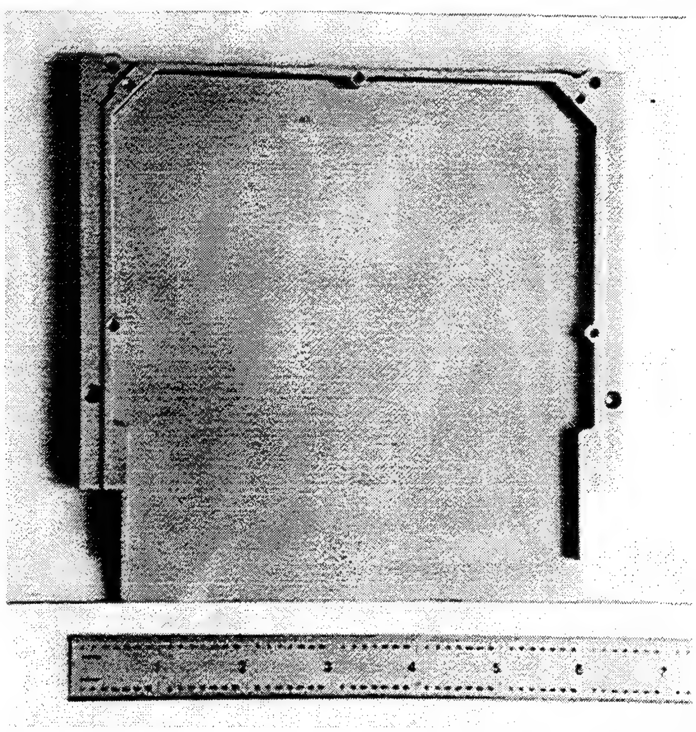
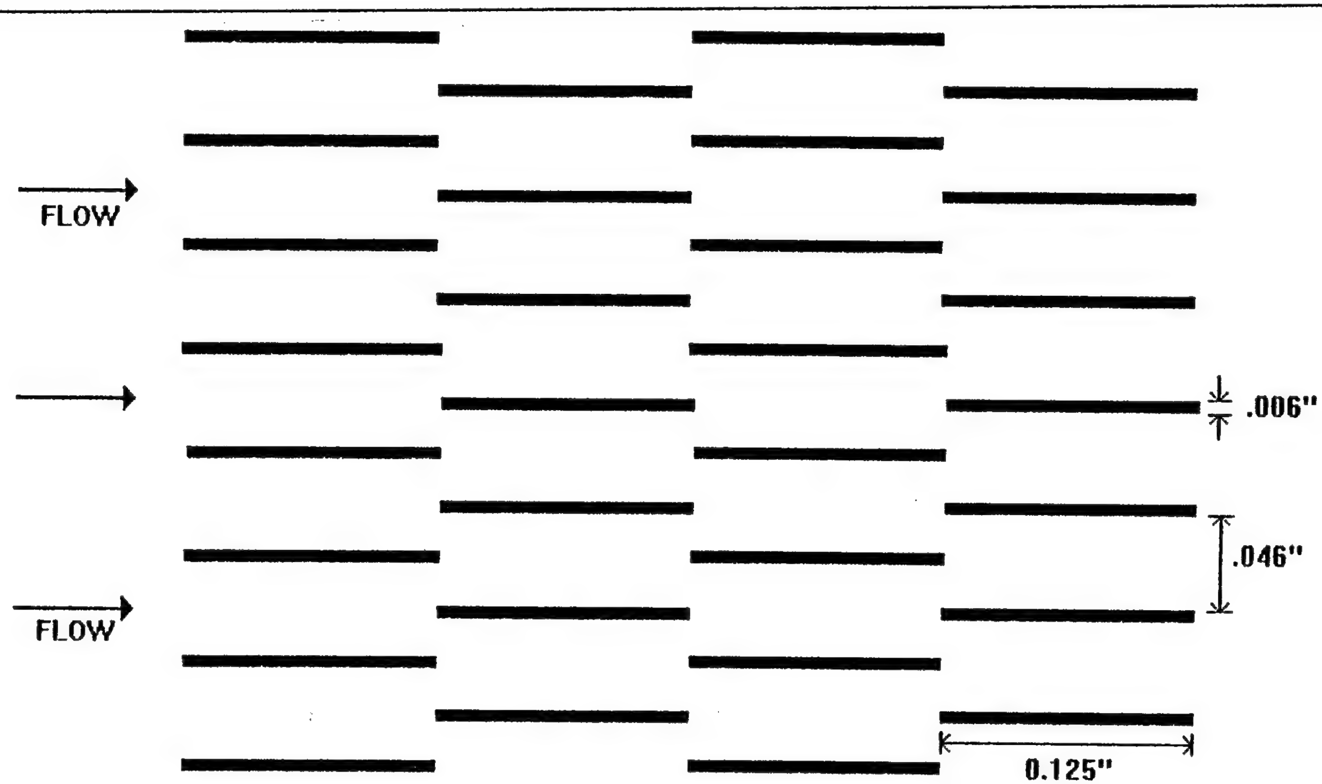


Figure 5. Top View of the Flow-Through Module.



Lance Length	: 0.125 inch
Fin Density	: 20 Fins/inch
Fin Height	: 0.06 inch
Fin thickness	: 0.006 inch
Fin Material	: 3003 Aluminum

Figure 6. Dimensions of the Offset Strip Fins in the Flow-Through Module [2].

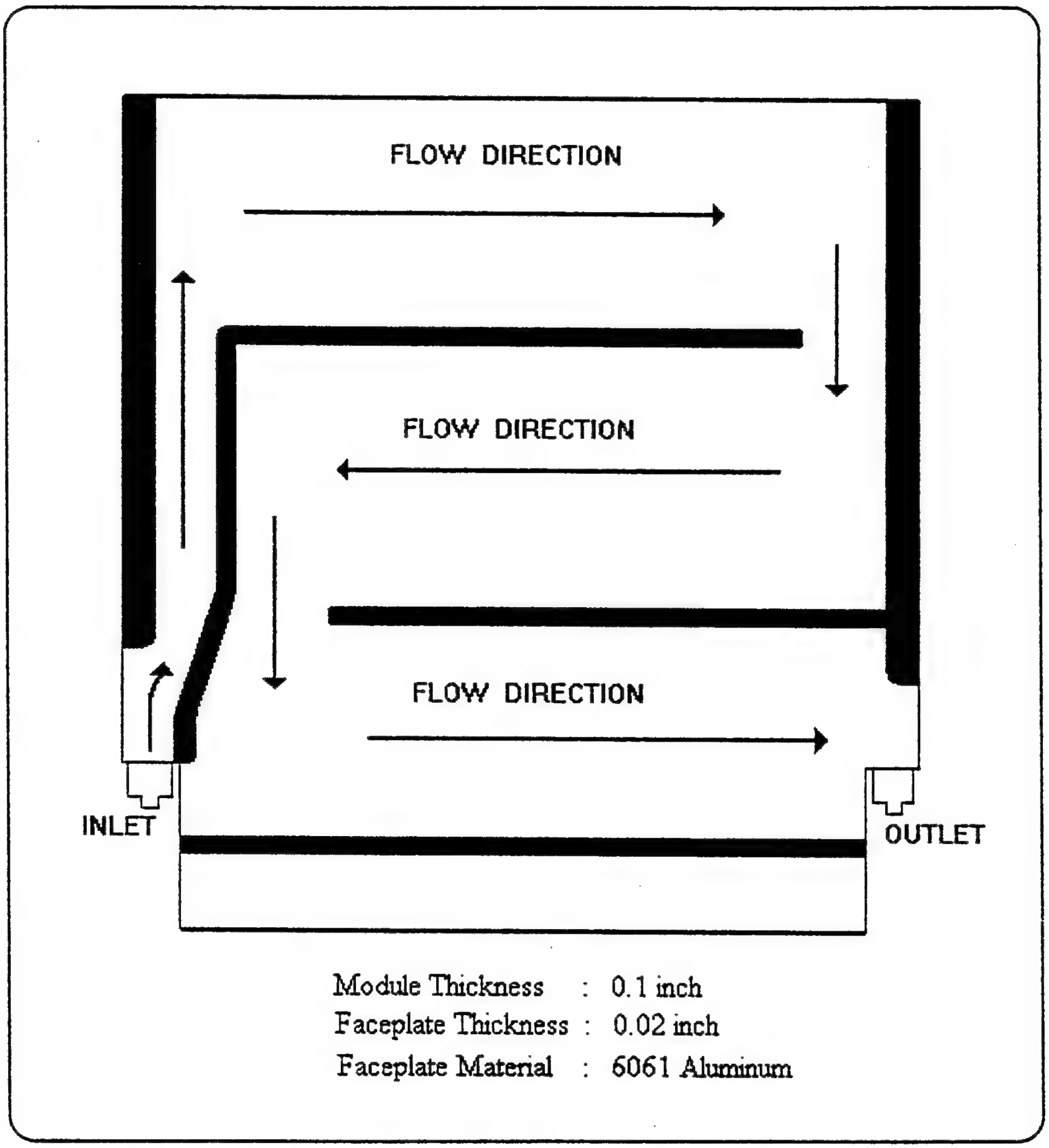


Figure 7. Fluid Flow Path within the FTM [2].

II. EXPERIMENTAL APPARATUS

A. SUPPORTING SYSTEM ASSEMBLY

The schematic diagram of the experimental setup, as shown in Figure -9 can be examined in two parts. The first part, which is called " Supporting System Assembly" consists of: Fluid Circulation, Power Distribution and Data Acquisition sub-systems. Each of these sub-systems and their components are as follows.

1. Fluid Circulation System

This section consisted of refrigeration bath, pump, variable speed control unit and flowmeter. The refrigerated circulating bath which provided the heat sink for the coolant was an Endocal RTE- 5. The pump and the drive speed control unit, manufactured by Masterflex could provide a maximum volumetric flow rate of 1 liter per minute. The coolant was pumped through flexible Tygon tubing. A flowmeter manufactured by Fischer and Porter was used to determine the flow rate. The Tygon tubing was connected to the Flow-Through Module through brass tubing, attached to the inlet and outlet ports of the module. The brass tubes were inserted into Tygon tubing and clamps were affixed to tighten the connections. Upon exiting the module the coolant returned to the refrigerated bath.

2. Power Distribution System

A Hewlett Packard 0-20V, 0-10A DC power supply was used to supply power to the heaters. Six heaters were affixed to the side-A and three heaters were affixed to the side-B, by using thermally conductive epoxy adhesive, Omega Bond 101. The heaters, manufactured by Minco, all wired in parallel, were 7.6 mm (0.3 in) by 38.1 mm (1.5 in) , kapton etched foil heaters.

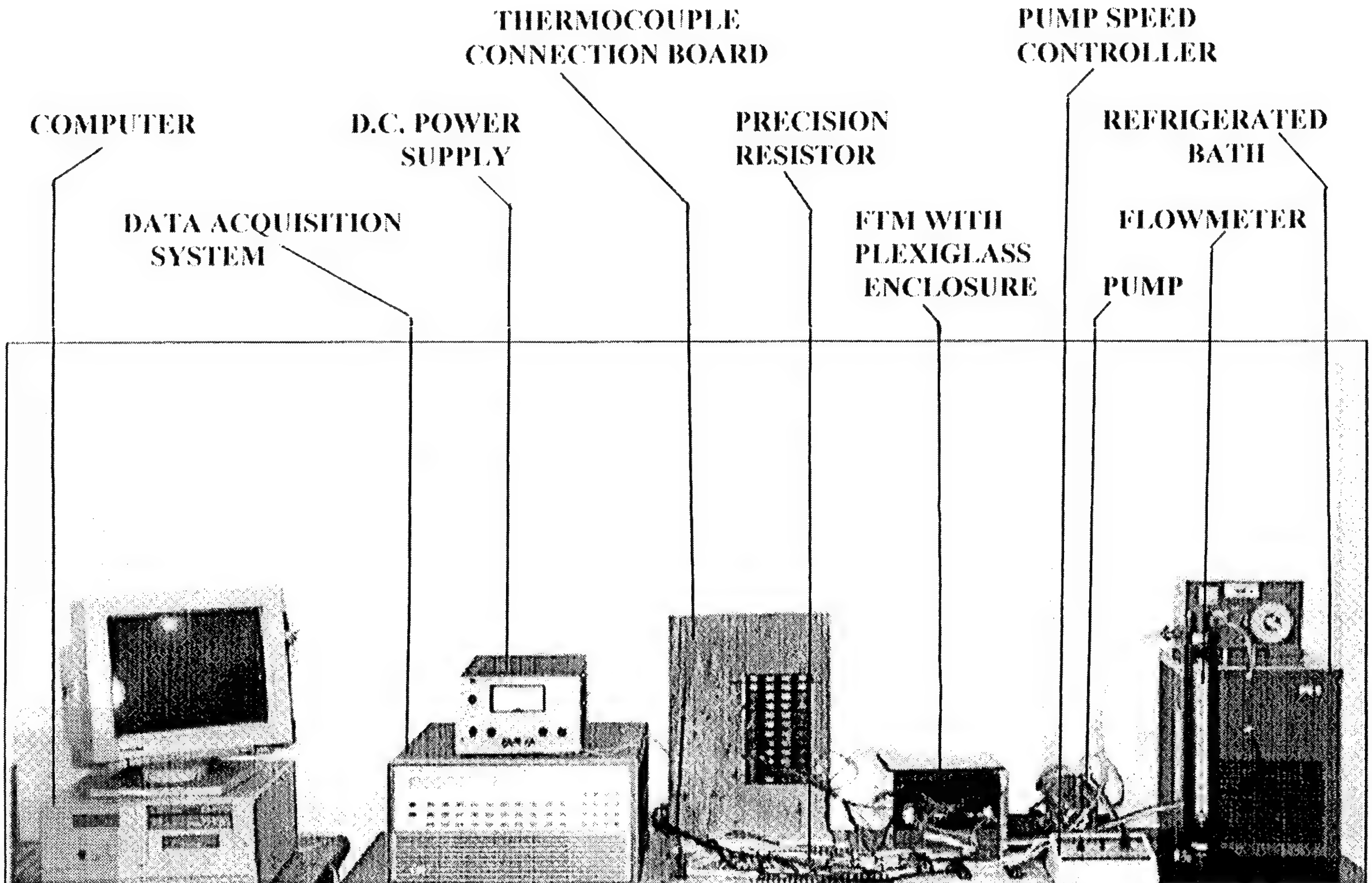


Figure 8. Experimental Setup

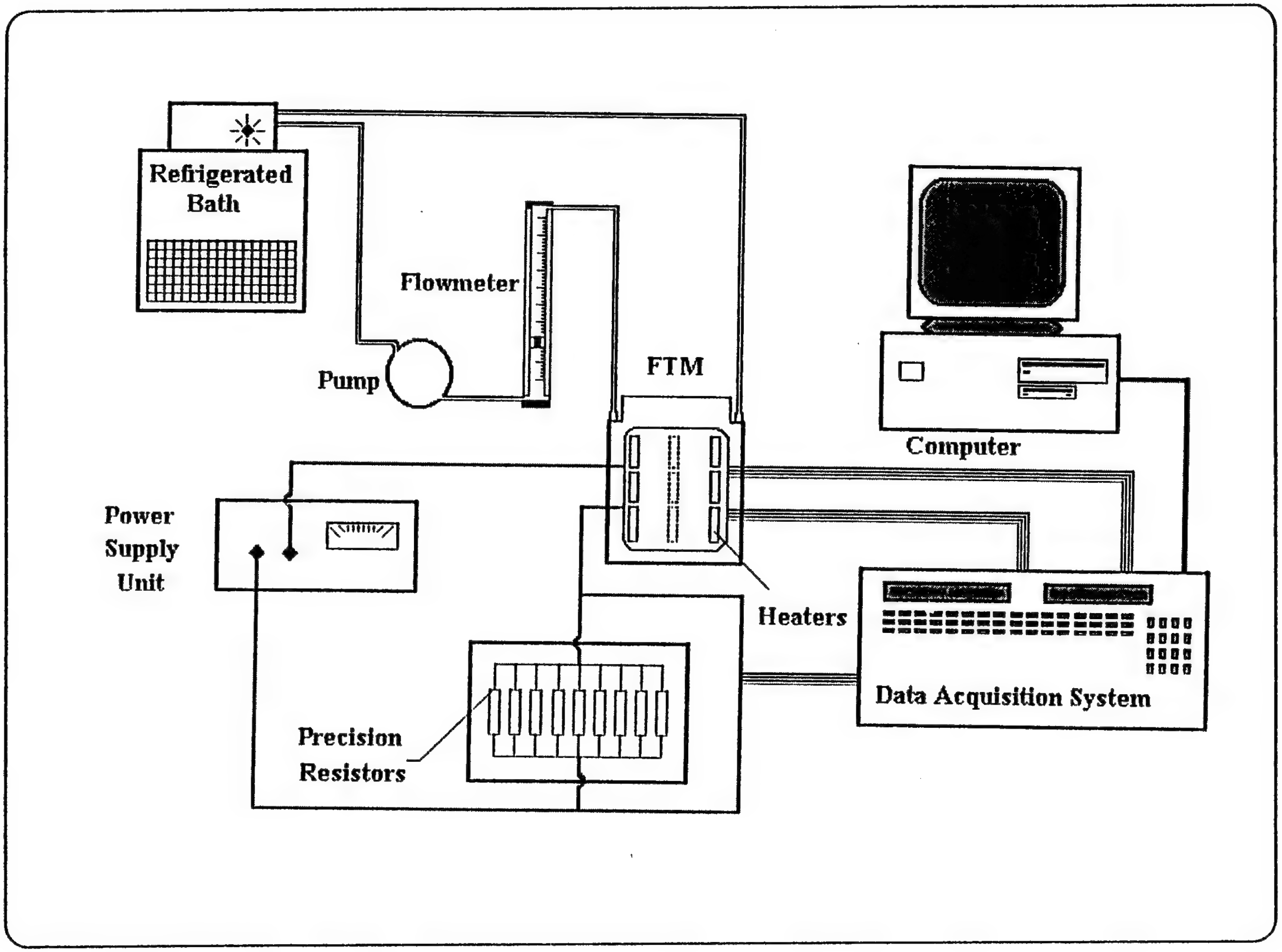


Figure 9. Schematic Drawing of the Experimental Setup.

The six heaters on side-A, as shown in Figure -10, were placed 5 cm (2 in) apart along the module flow paths by affixing two heaters on each flow path. The three heaters on side-B, as shown in Figure -11, were placed on the centerline of the module. the rows of heaters were 1.25 cm (0.5 in) apart from each other. Each heater had an effective heated area of 1.94 cm^2 (0.3 in^2) and a resistance of 20.7 ohms ± 10 %.

In order to measure the current passing through each heater, thermally stable precision resistors were connected in series with each heater. Prior to connecting, each resistor was calibrated by using a Rosemount 920 A Commutating Bridge to determine its resistance precisely. Six of the resistors, connected in series with the six heaters on side-A were 0.487 ohms ± 1 % and the other three resistors connected in series with the three heaters on side-B were 0.500 ohms ± 1 %.

A Hewlett Packard 44701A digital voltmeter which was a part of the HP 3852A Data Acquisition Control Unit, was used to determine the voltage drops across the heaters and the precision resistors. All of the 18 measurements, voltage drops across the heaters and precision resistors were measured by utilizing an HP 44705A 20 channel multiplexer.

3. Data Acquisition System

A Hewlett Packard 3852A Data Acquisition / Control Unit was used to measure the voltages and temperatures. In order to be able communicate with the data Acquisition / Control Unit through a computer, an interface board, GPIB-PCIIA IEEE-488, manufactured by National Instruments had been installed in a Personal Computer. A program written in QBASIC code, attached as Appendix-D, was used to acquire temperature and voltage data. An HP 44708A 20 channel relay type multiplexer was used for temperature measurements. The experiments were conducted first for side-A and then repeated for side-B, since all the 20 channels of the HP44708A were utilized during the experiments. Thermocouple locations for both sides of the FTM were shown, schematically in Figures 12-a and 12-b.

Fifteen of the thermocouples were attached onto the module itself and two thermocouples were placed at the inlet and the outlet of the module. Two thermocouples

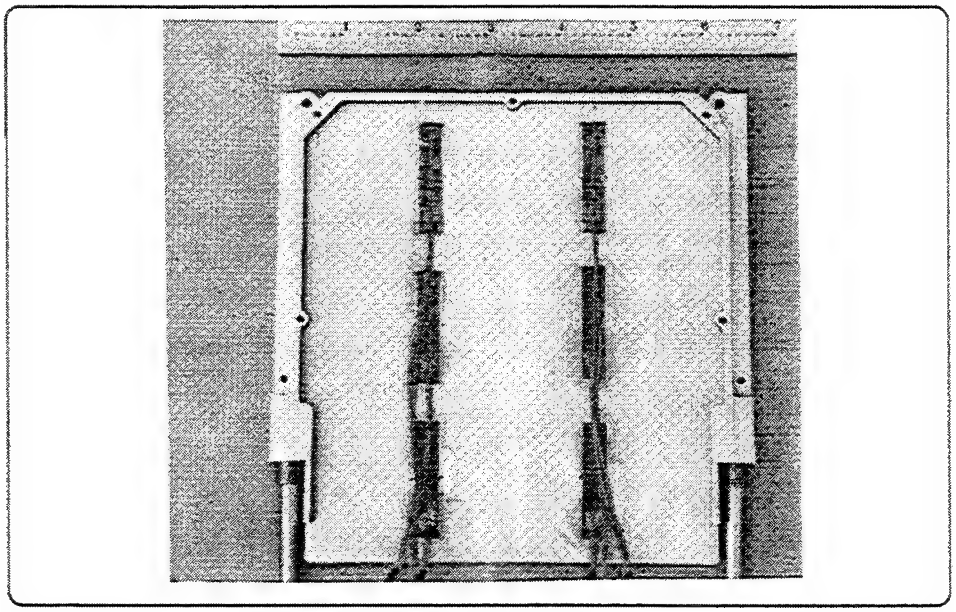


Figure 10. Heater Locations on the FTM for Side - A.

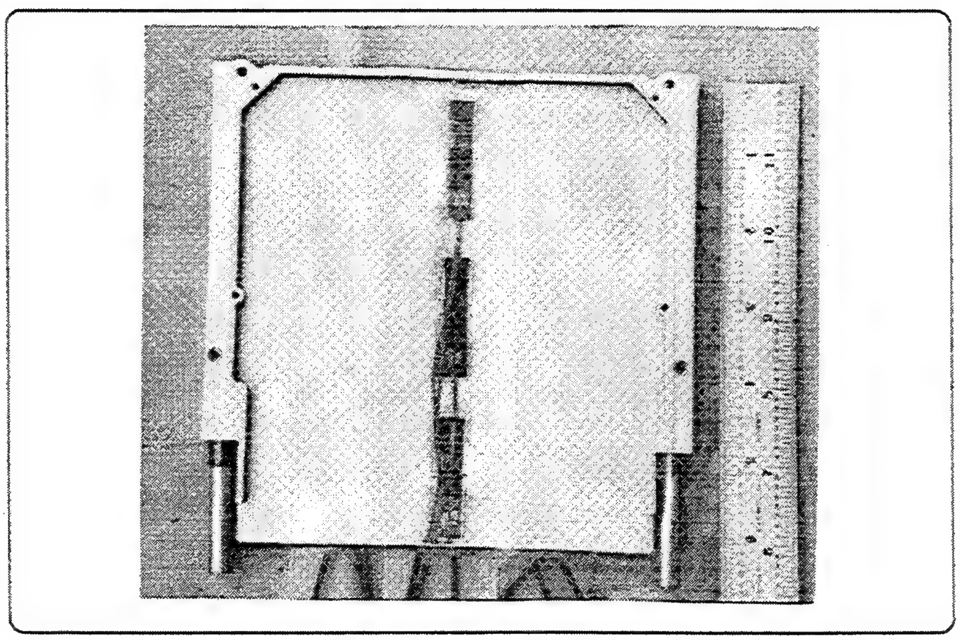


Figure 11. Heater Locations on the FTM for Side - B.

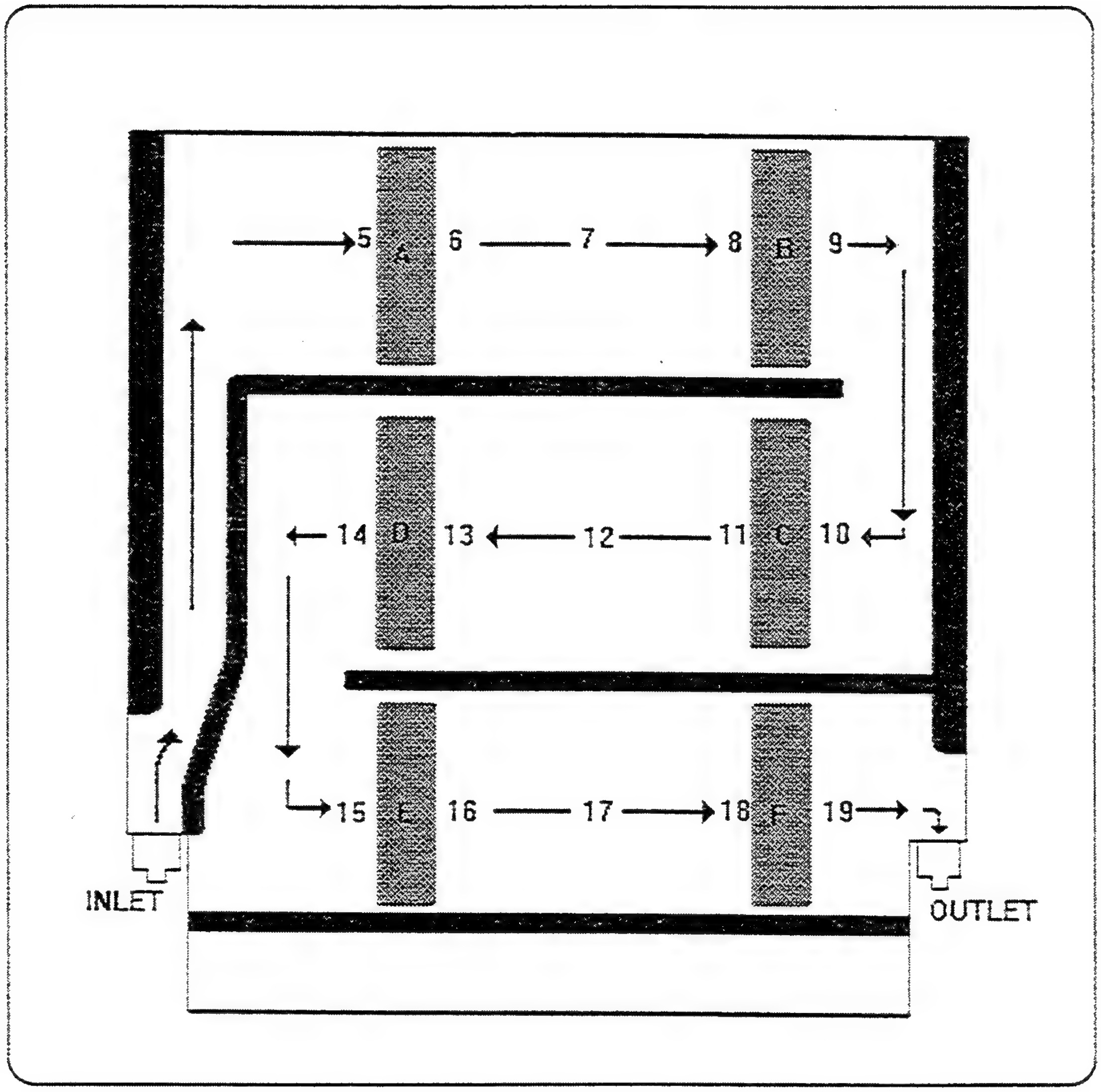


Figure 12-a. Schematic Drawing of Thermocouple and Heater Locations on Side-A of the Flow-Through Module.

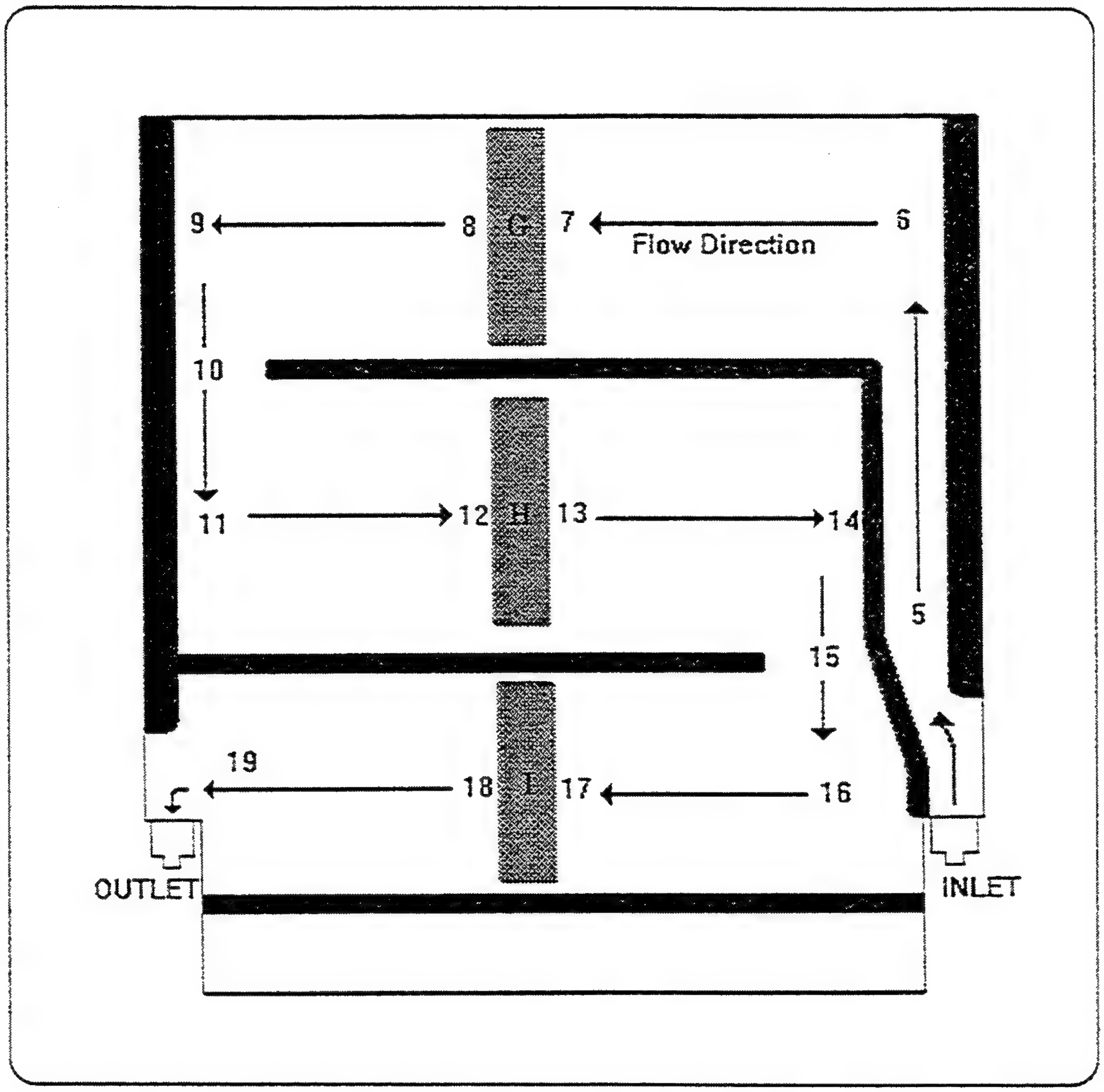


Figure 12-b. Schematic Drawing of Thermocouple and Heater Locations on Side-B of the Flow-Through Module.

Fifteen of the thermocouples were attached onto the module itself and two thermocouples were placed at the inlet and the outlet of the module. Two thermocouples were placed in the insulation layers to estimate the heat loss. An additional thermocouple was used either to measure ambient room temperature or coolant temperature in the refrigerated bath. Thermocouple extensions were fed into channel numbers 0 through 19 of the HP44708A in the data acquisition system.

Voltage drops across the heaters were measured by the channels 0 through 8 of the HP44705A multiplexer, corresponded to heaters A through I respectively. On the other hand , precision resistor voltages were measured by utilizing the channels 9 through 17 of the HP44705A mutiplexer.

B. TEST SECTION ASSEMBLY

1. Housing of the Flow-Through Module

The Flow-Through Module was supported in a horizontal position by a plexiglass enclosure. The FTM was insulated on all sides, inside the plexiglass enclosure, by using 0.75 inch (1.91 cm) thick, black foam type insulation. Two layers of insulation were placed on top and bottom sides of the FTM and one layer of insulation was placed along the edges of the module as well. The front side of the enclosure was open for wiring and tubing connections [1].

2. Implementation of Thermocouples

Thermocouples affixed onto the surface of the module were, T-type Copper-Constantan, flat, 5 mil thick, foil type, cement-on thermocouples. They could be placed very close to the heaters. Copper leads were soldered to the thermocouple extension wire and the constantan leads were resistance welded to the extension wire. These connections were wrapped using kapton tape to keep them separate. Thermocouples were affixed by using the same kapton tape.

T- type thermocouple probes were used to measure the coolant temperature at the inlet and outlet of the module. These thermocouples were 8 mil thick and are welded to form a "bead" junction.

Thermocouples used to measure the temperatures at the top and bottom sides of the insulation were also 8 mil thick are welded T- type copper constantan thermocouples. They were affixed onto the insulation by using electrical tape.

Thermocouples used at the inlet and outlet of the module for coolant temperature measurements, were calibrated by using a Rosemount 920A commutating bridge and a constant temperature ethylene glycol bath.

III. EXPERIMENTAL PROCEDURES

A. CALCULATION OF COOLANT THERMOPHYSICAL PROPERTIES

Temperatures at the inlet an outlet of the module were measured 30 times during each run in a 20-second time interval. The average values of both inlet and outlet temperatures were computed and the mean of these two values was utilized to calculate the thermophysical properties of the coolant, Brayco Micronic 889.

1. Density (g/ml)

Densities of the coolant at various temperatures provided by the manufacturer (Castrol) were curve fitted and the polynomial obtained by this process was used to calculate the density at any temperature. Data Supplied by Castrol is tabulated in Table 1.

TEMPERATURE ($^{\circ}$C)	DENSITY (g / ml)
0 °C (32 °F)	0.811
20 °C (68 °F)	0.794
40 °C (104 ° F)	0.777
100 ° C (212 °F)	0.723
160 ° C (320 ° F)	0.661

Table 1. Density Data of the Coolant, Brayco Micronic 889 [3] .

The curve obtained is shown in Figure 13. The second order polynomial the curve fit is as follows:

$$\rho = -8.8216 * 10^{-7} * T_{avg}^{2} - 7.9251 * T_{avg} + 0.81055 \qquad \text{g / ml} \qquad (1)$$

where T_{avg} is the average temperature differential of the coolant between inlet and outlet of the FTM in degrees Celsius.

$$T_{avg} = \frac{T_{inlet} + T_{outlet}}{2} = \frac{T(3) + T(4)}{2} \qquad (2)$$

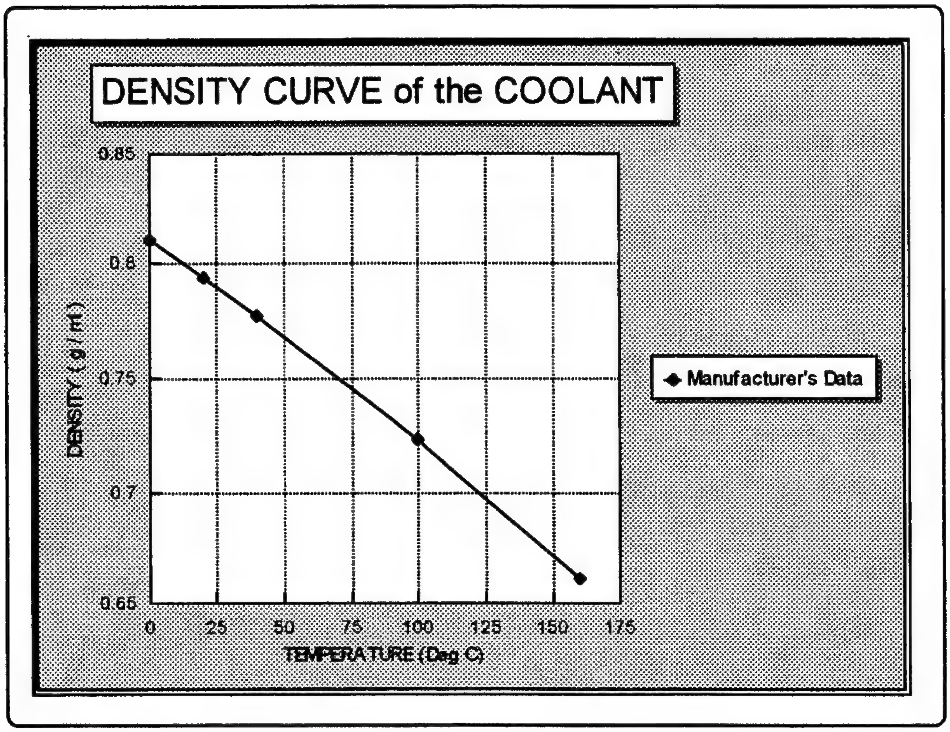


Figure 13. Density Curve of the Coolant Brayco Micronic 889.

2. Specific Heat (J / g °C)

In the previous study [1], certain inconsistencies in the energy balancearose. After thorough investigation it was hypothesized that the values for specific heat of the PAO were not accurate. To obtain accurate values of the specific heat, samples of the PAO, were sent to Delsen Testing Laboratories Inc.,for testing and measurement of the specific heat. A second order polynomial curve fit to this data is given as follows:

$$c_p = 3.5284 * 10^{-4} * T_{avg}^2 + 1.0466 * 10^{-3} * T_{avg} + 0.46955 \ cal/g\,°C \qquad (3)$$

A comparison of the Delsen Laboratories data with the PAO manufacturer's data is given in Table 2 and Figure 14.

TEMPERATURE	SPECIFIC HEAT (CASTROL, cal/g ° C)	TEMPERATURE	SPECIFIC HEAT (LAB'S DATA, cal/g ° C)
-18 ° C (0 ° F)	0.49	10°C (50°F)	0.48
10 ° C (50° F)	0.52	38°C (100 ° F)	0.51
38 ° C (100°F)	0.54	66 ° C (151 °F)	0.54
93 °C (200 °F)	0.58	93 ° C (200 ° F)	0.57

Table 2 . Specific Heat Values of the Coolant (by Castrol and Delsen Laboratories).

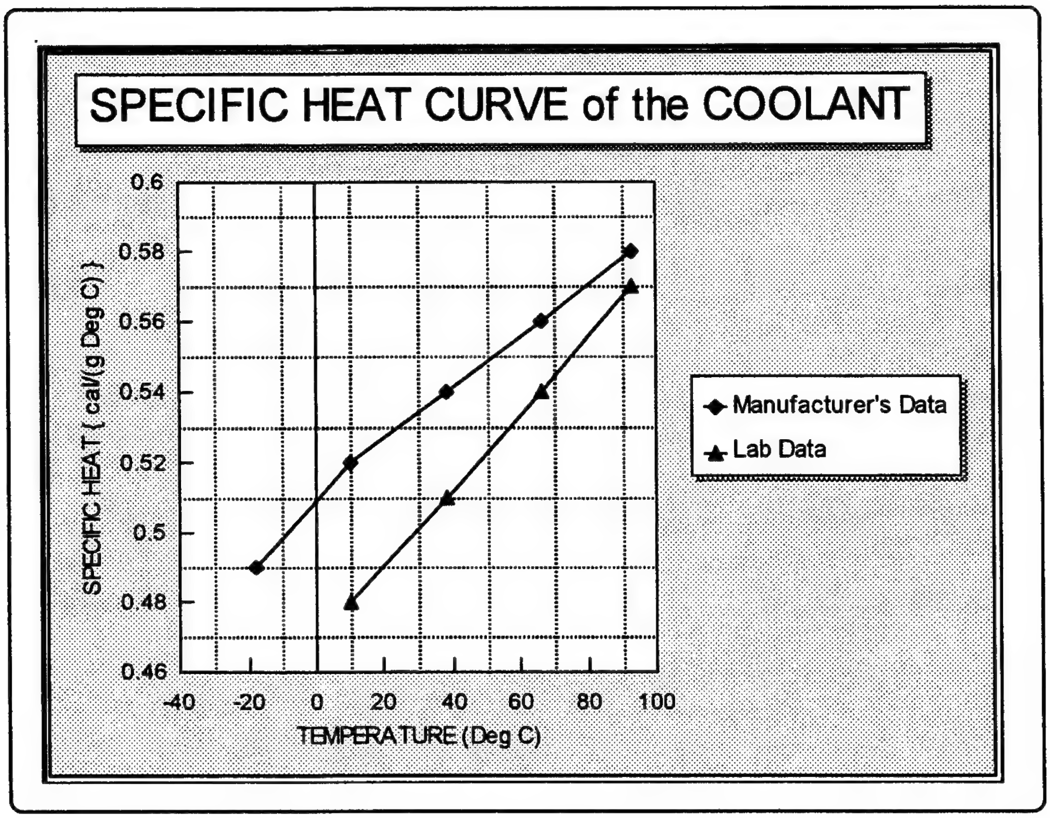


Figure 14. Specific Heat Comparison of Brayco Micronic 889.

3. Kinematic Viscosity (m^2/s)

Manufacturer's data was utilized to acquire a relationship for kinematic viscosity of the coolant in the temperature range of the experiments. Data supplied by Castrol is tabulated in Table 3 and plotted in Figure 15. With some uncertainty kinematic viscosity was assumed to be changing linearly in this temperature range. According to the data shown in Appendix -C, the relationship for the kinematic viscosity of Brayco Micronic 889 was determined as follows:

$$\nu = (-3.185 \times T + 5.2) \times 10^{-6} \ \text{m}^2/\text{s} \tag{4}$$

TEMPERATURE (° C)	KINEMATIC VISCOSITY (m^2/s)$*10^{-6}$
100 ° C	1.7
40 ° C	5.2
-40 ° C	260
-54 ° C	1,200

Table 3. Kinematic Viscosity Data of Brayco Micronic 889 [3].

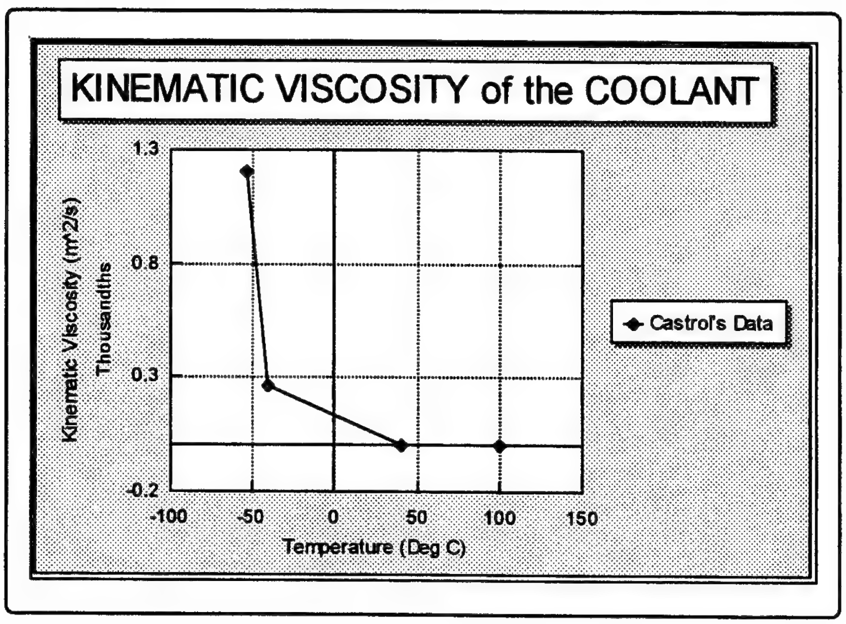


Figure 15. Kinematic Viscosity Curve of Brayco Micronic 889.

B. FLOWMETER CALIBRATION PROCEDURE

Flowmeter calibration was performed by measuring the time intervals for 1 and two liters of coolant to fill a scaled container for 10 percent increments of the flow rates from 10% to 100%. The data obtained are tabulated in Table 4. The average of two of the resulting measurements was taken and the data obtained was curve fitted. The calibration curve of the flowmeter for the coolant, Brayco Micronic 889 is shown in Figure 16. The fourth order polynomial curve fit is given below:

$$\dot{Q} = 2.7178 \times 10^{-5}\alpha^4 - 6.02 \times 10^{-3}\alpha^3 + 0.422\alpha^2 + 4.1837\alpha - 8.07 \quad \text{ml/min} \qquad (5)$$

where α is the flowmeter reading in percentage.

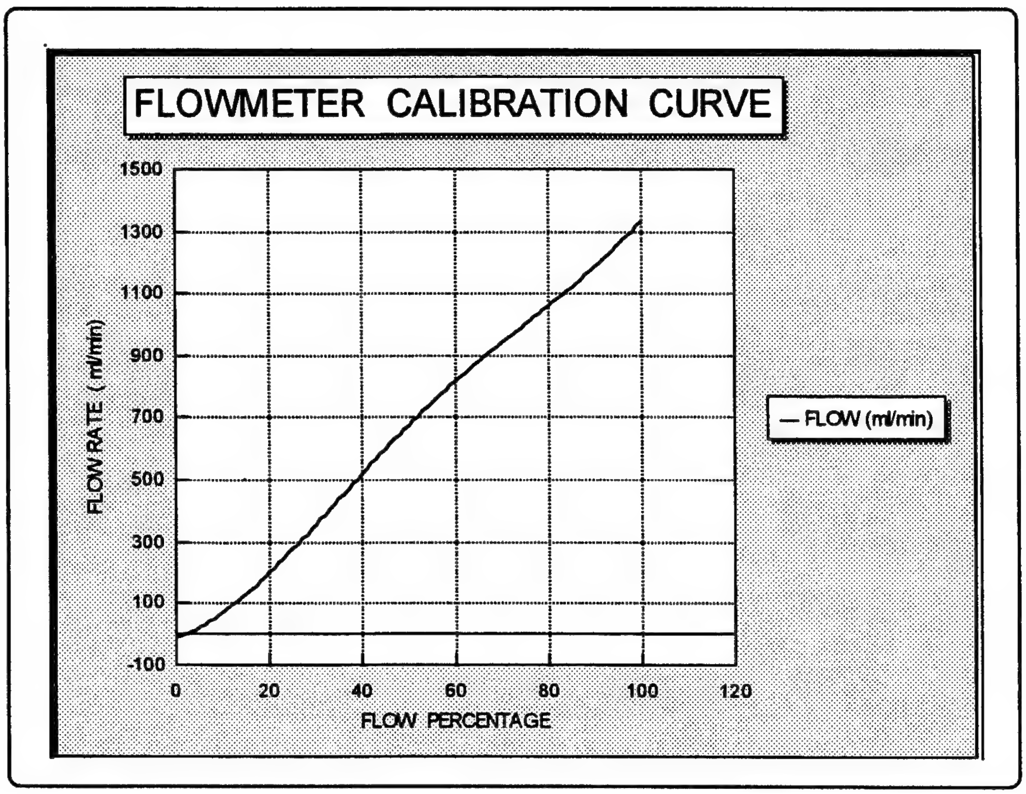


Figure 16. Flowmeter Calibration Curve for the Coolant , Brayco Micronic 889.

FLOWMETER CALIBRATION DATA

	Run - 1		*Run - 2*		
Flow %	min / L	ml / min	min / 2L	ml / min	Average
0	0	0	0	0	0
10	15.71	63.7	31.91	62.7	63.2
15	7.87	127.1	15.95	125.4	126.25
20	5.4	185.2	10.95	182.6	183.9
25	3.57	280.1	7.14	280.1	280.1
30	2.67	374.5	5.4	370.4	372.45
35	2.24	446.4	4.45	449.4	447.9
40	1.87	534.8	3.74	534.8	534.8
45	1.7	588.2	3.35	597	592.6
50	1.48	675.7	2.98	671.1	673.4
55	1.35	740.7	2.7	740.7	740.7
60	1.23	813	2.49	803.2	808.1
65	1.14	877.2	2.26	885	881.1
70	1.06	943.4	2.13	939	941.2
75	0.98	1020.4	2.01	995	1007.7
80	0.94	1063.8	1.9	1052.6	1058.2
85	0.88	1136.4	1.79	1117.3	1126.85
90	0.82	1219.5	1.66	1204.8	1212.15
95	0.81	1234.6	1.58	1265.8	1250.2
100	0.77	1298.7	1.52	1315.8	1307.25

FLOWMETER SETTINGS

Flow (ml/min)	*Flow %*
50.3	9.4
99.9	13.5
150.3	17
200.6	20.2
250.1	23.2
300.7	26.2
349.8	29.1
400	32.1
449.8	35.1
499.7	38.2
549.5	41.4
600.6	44.8
649.6	48.2
699.5	51.8
750.4	55.6
799.8	59.4
850.8	63.4
900.2	67.3
949.7	71.2
999.8	75.1
1050.6	79
1100.8	82.8
1150.1	86.5
1200.4	90.3
1250.8	94.2
1300.5	98.7
1319.6	100

	Regression Output:	**Run - 1**
Constant		-43.97
Std Err of Y Est		28.391
R Squared		**0.9956**
No. of Observations		20
Degrees of Freedom		18
X Coefficient(s)	13.88	
Std Err of Coef.	0.217	

	Regression Output:	**Run - 2**
Constant		-46.12
Std Err of Y Est		25.6
R Squared		**0.9964**
No. of Observations		20
Degrees of Freedom		18
X Coefficient(s)	13.89	
Std Err of Coef.	0.196	

Regression Output:		**Flow Settings**
Constant		4.291
Std Err of Y Est		1.5115
R Squared		**0.9972**
No. of Observations		27
Degrees of Freedom		25
X Coefficient(s)	0.071	
Std Err of Coef.	0.001	

Table 4. Flowmeter Calibration Data and Regression Outputs.

C. COLLECTION AND ANALYSIS OF THE DATA

In this study two different sets of experiments were conducted: one for Side- A and one for Side- B of the Flow-Through Module. The naming of the sides of the module as A and B was arbitrary. For the first set of experiments, thermocouples were affixed to Side- A where 6 heaters were located. Nine different power settings from 20 W to 100 W in 10 Watt increments and seven different flow rates from 350 ml/min to 950 ml/min in 100 ml/min increments were tested.

During the second set of experiments, which were for Side- B where 3 heaters were located, 5 different power settings from 20 W to 100 W in 20 Watt increments were tested. The flow rates were the same as those used for the first set of experiments. Temperature data were observed on the monitor of the PC to determine when steady state had been achieved. Steady state was assumed to be achieved when the average surface temperature and the temperature difference of the coolant between the thermocouples located at the inlet and the outlet of the module varied by no more than 0.02 ^{0}C over a 5-minute period. Voltage measurements, thermocouple readings, and a series of 30 coolant inlet and outlet temperature readings were taken over a period of 20 seconds and the data was recorded. Depending upon the power setting and flow rate combination, steady state was achieved in 10 to 40 minutes. After saving the data to a file, the flow rate was adjusted to the next value to continue the procedure.

It was generally observed that steady state was more rapidly achieved as the flow rate got higher. Flow rates were increased in 100 ml/min increments from 350 ml/min to 950 ml/min. The flow began to pulse at lower flow rates. Therefore 350 ml/min was taken as the lower limit for the flowmeter settings.

Power settings were adjusted using the HP power supply. The total amount of power supplied was monitored and adjusted until the desired value was achieved. Power settings were varied in the range from 20 W to 100 W by either 10 W or 20 Watt increments. The diagram of the circuit formed by heaters and precision resistors was

shown in Figure-17. The variation of resistances could be 10 % in the heaters and 1 % in precision resistors according to the manufacturers' data.

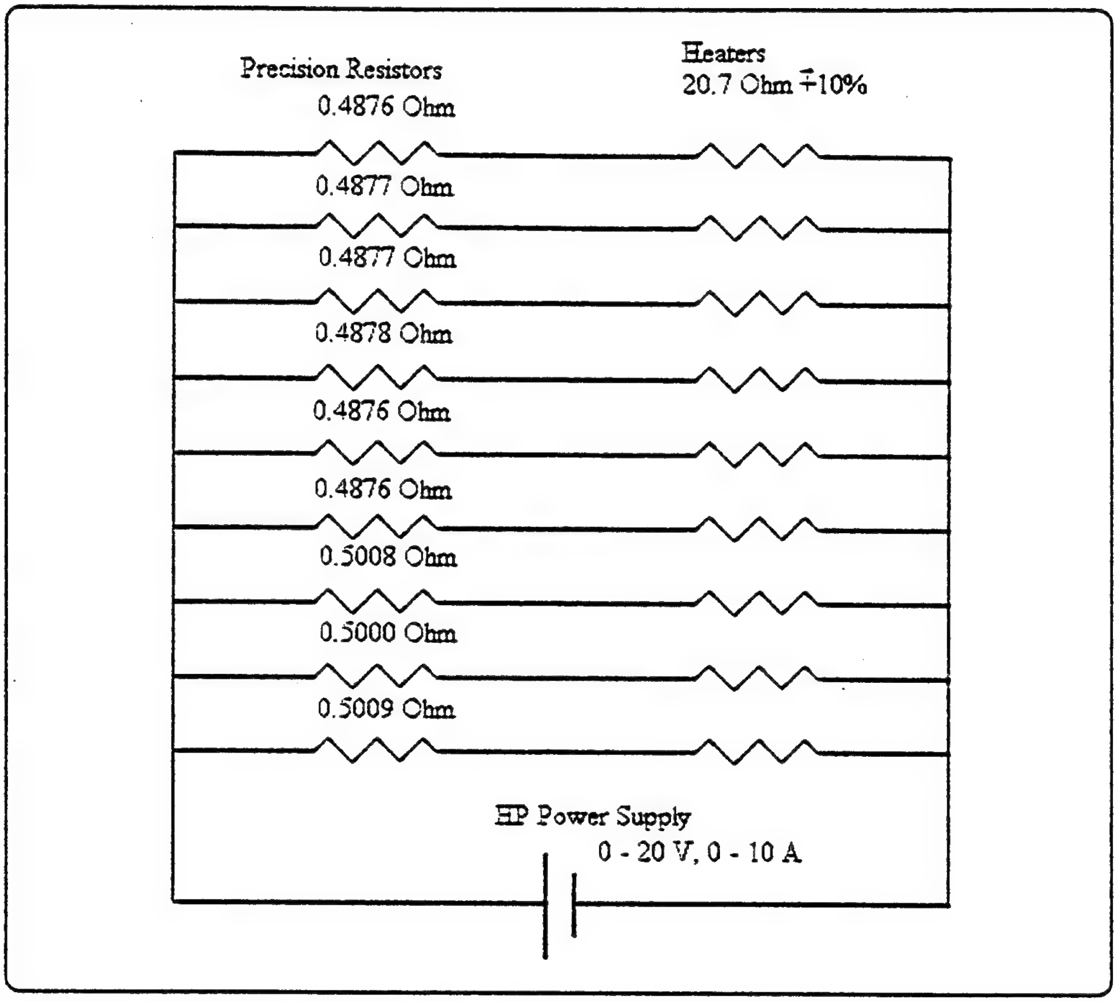


Figure 17. Schematic Drawing of the Electrical Circuit Formed by Heaters and Precision Resistors.

1. Calculation of Total Power

Data was analyzed by calculating the total power supplied by the heaters and comparing it with the sum of heat dissipated by the coolant and the heat lost through the insulation.

$$P_t = q_{fluid} + q_{loss} \tag{6}$$

Current passing through each heater was calculated by utilizing the precision resistors, since each heater was connected in series as shown in Figure-17.

$$I_h = I_p = \frac{V_p}{R_p} \qquad (7)$$

Thus 9 different current values were obtained as follows;

$$I_h(i) = I_p(i) = \frac{V_p(i)}{R_p(i)} \quad \mathrm{i = 0\ to\ 8} \qquad (8)$$

Then these current values used in the following equation to get the power supplied to each heater;

$$P_h(i) = V_h(i) \times I_h(i) \quad \mathrm{i = 0\ to\ 8} \qquad (9)$$

As a result the total power supplied to the module was calculated as follows:

$$P_t = \sum_{i=0}^{8} P_h(i) \quad \text{Watts} \qquad (10)$$

The heat flux generated by each heater in Watts/cm^2 was calculated for each power setting by the following equation:

$$q'' = \frac{1}{A_{eff}} \frac{P_t}{9} \quad (\text{Watts / cm}^2) \qquad (11)$$

where A_{eff} = 1.94 cm^2 Effective Heater area.

The values of total power and heat flux per heater for each power setting were tabulated in Table 5.

Power Setting Side - A	Power Setting Side - B	P_{total} (W)	Heat Flux per Heater (W/cm^2)
1	1	20	1.15
2		30	1.72
3	2	40	2.3
4		50	2.86
5	3	60	3.44
6		70	4.01
7	4	80	4.58
8		90	5.15
9	5	100	5.73

Table 5 . Power Settings for Both Set of Experiments.

2. Calculation of Heat Dissipation

a. Average Temperature Differential

The temperature of the coolant was measured at the inlet and outlet of the module for 30 times during each run of experiments. The average of both inlet and outlet temperatures were calculated by the program written in QBASIC for the data acquisition system as follows;

$$\Delta T_{diff} = \sum_{i=1}^{30} \frac{T_i(4) - T_i(3)}{30} \tag{12}$$

b. Heat Dissipated by the Coolant

The coolant dissipated almost all of the heat supplied by the heaters to the flow-Through module. The following equation was utilized to calculate the heat transferred to the coolant;

$$q_{fluid} = \frac{\rho \dot{Q} c_p \Delta \overline{T}_{diff}}{60} \tag{13}$$

where

ρ : Density (g / ml)

$\dot{Q}$: Flow rate (ml / min)

c_p : Specific Heat (J / g ^{0}C)

ΔT_{avg} : Average Temperature Differential (^{0} C)

c. Average Module Surface Temperature

The temperature on the surface of the module was measured at 15 different locations for each set of experiments. (Side- A and Side- B). The average of these fifteen temperatures were calculated for data analyzing purposes as follows:

$$\Delta \bar{T}_{surf} = \frac{\sum_{i=5}^{19} T(i)}{15} \tag{14}$$

3. Heat Loss Through the Insulation

Some amount of heat was conducted through the insulation in either direction depending on the power setting and flow rate. Average module surface temperature was utilized in calculating the heat losses through the insulation as follows;

$$q_{loss} = \frac{kA}{L}\left[\Delta \bar{T}_{surf} - T(2)\right] \qquad \text{Watts} \tag{15}$$

where

k = 0.04 W/m ^{0}C Thermal Conductivity of the Insulation

A = 5.66 in * 6 in = 33.96 in^2 = 0.0219 m^2 Surface Area of the Insulation

L = 0.75 in = 0.0191 m Insulation Thickness

finally, the difference in energy balance is calculated as follows:

$$\Delta q = P_t - q_{fluid} - q_{loss} \qquad \text{Watts} \tag{16}$$

IV. EXPERIMENTAL RESULTS

A. HEAT TRANSFER DATA

A program written in QBASIC code was utilized to obtain experimental data, (voltages and temperatures) through the data acquisition ststem. Voltage and temperature values were used to calculate the following information in the Tables 6 through 41;

- Heat suplied to the FTM by each heater, in watts.
- Total power supplied to the module, in watts.
- Average module surface temperature, in ^{0}C.
- Average temperatures of the coolant at the inlet and outlet of the module and the differential of these two temperature values, in ^{0}C.
- Thermophysical properties, density and specific heat of the coolant, Brayco Micronic 889, in g / ml and in J / g ^{0}C respectively.
- Heat dissipated by the coolant, in watts.
- Heat losses through the insulation, in watts.

Thermocouples 5 through 19 were used to measure the surface temperatures of the module at 15 different locations. These temperature values are plotted in Figures 19 through 27 and 33 through 37 for both sets of experiments conducted for Side- A and Side- B, respectively.

The graphs of average temperature differential of the coolant between inlet and outlet vs. flow rate are shown in Figures-28 and 38 for Side -A and Side -B respectively. Logarithmic scales of the same graphs are shown in Figures 29 and 39. Average Module surface temperature vs. flow rate is graphed for both Side -A and Side -B in Figures 30 and 40 respectively. Also logarithmic scales of these graphs are plotted in Figures 31 and 41.Total power supplied to the module was compared with the sum of heat dissipated by the coolant and the heat lost through the insulation and the graphs are shown in Figures 32 and 42 for both sides of the FTM.

FTM SIDE - A

POWER SETTING # 1 (20 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	2.258	2.259	2.26	2.261	2.256	2.257	2.257
Heater -2	2.246	2.247	2.249	2.25	2.245	2.245	2.245
Heater -3	2.229	2.23	2.232	2.233	2.228	2.228	2.228
Heater -4	2.162	2.164	2.165	2.166	2.161	2.162	2.162
Heater -5	2.223	2.224	2.226	2.227	2.222	2.222	2.222
Heater -6	2.241	2.243	2.244	2.245	2.24	2.241	2.241
Heater -7	2.226	2.227	2.229	2.23	2.225	2.225	2.225
Heater -8	2.227	2.228	2.23	2.23	2.226	2.226	2.226
Heater -9	2.257	2.258	2.26	2.261	2.256	2.256	2.257
TOT. POW.	**20.069**	**20.08**	**20.095**	**20.103**	**20.059**	**20.062**	**20.063**
Av. Sur. T.	23.23	22.91	22.17	21.85	21.61	21.42	21.24
T in	21.294	21.302	20.497	20.558	20.341	20.165	20.042
T out	23.43	22.949	21.849	21.728	21.461	21.216	21.004
DENSITY	0.7924	0.7926	0.7934	0.7934	0.7936	0.7938	0.7939
SP.HEAT	2.0633	2.0622	2.058	2.0578	2.0568	2.0558	2.0551
Q fluid	20.37	20.19	20.24	20.69	22.85	24.3	24.85
Q ins	0.01	-0.04	-0.04	-0.06	-0.06	-0.07	-0.08
Q total	**20.38**	**20.15**	**20.2**	**20.63**	**22.79**	**24.23**	**24.77**
DELTA Q	0.311	0.07	0.105	0.527	2.731	4.168	4.707
DT ins	0.14	-0.89	-0.84	-1.28	-1.37	-1.49	-1.66
DT fluid	2.14	1.65	1.48	1.17	1.12	1.05	0.96

THERMOCOUPLE READINGS

T/C -0	23.09	23.8	23.01	23.13	22.98	22.91	22.9
T/C -1	23.06	22.73	23.44	21.78	21.56	21.47	21.39
T/C -2	19.87	19.75	19.49	19.3	19.08	19.05	19.13
T/C -3	21.29	21.3	20.6	20.56	20.34	20.17	20.04
T/C -4	23.43	22.95	22.08	21.73	21.46	21.22	21
T/C -5	21.76	21.7	21.05	20.89	20.67	20.5	20.36
T/C -6	22.24	22.12	21.43	21.23	21	20.85	20.67
T/C -7	22.75	22.58	21.84	21.63	21.42	21.24	21.09
T/C -8	22.77	22.55	21.88	21.61	21.35	21.17	20.99
T/C -9	22.81	22.6	22.15	21.59	21.35	21.14	20.98
T/C -10	22.93	22.62	21.91	21.6	21.41	21.19	21.01
T/C -11	23.51	23.14	22.52	22.07	21.86	21.69	21.54
T/C -12	23.42	23.05	22.24	21.96	21.73	21.51	21.34
T/C -13	23.32	22.95	22.11	21.88	21.6	21.37	21.2
T/C -14	23.26	22.88	22.02	21.73	21.43	21.24	21.02
T/C -15	23.25	22.86	22.05	21.81	21.54	21.38	21.18
T/C -16	23.74	23.32	22.69	22.21	21.98	21.79	21.62
T/C -17	24.06	23.6	22.73	22.41	22.13	21.87	21.65
T/C -18	24.38	23.89	23.01	22.64	22.38	22.22	22
T/C -19	24.21	23.73	22.92	22.51	22.25	22.07	21.89

Table 6. Power and Temperature Data for Side - A, at Power Setting 1

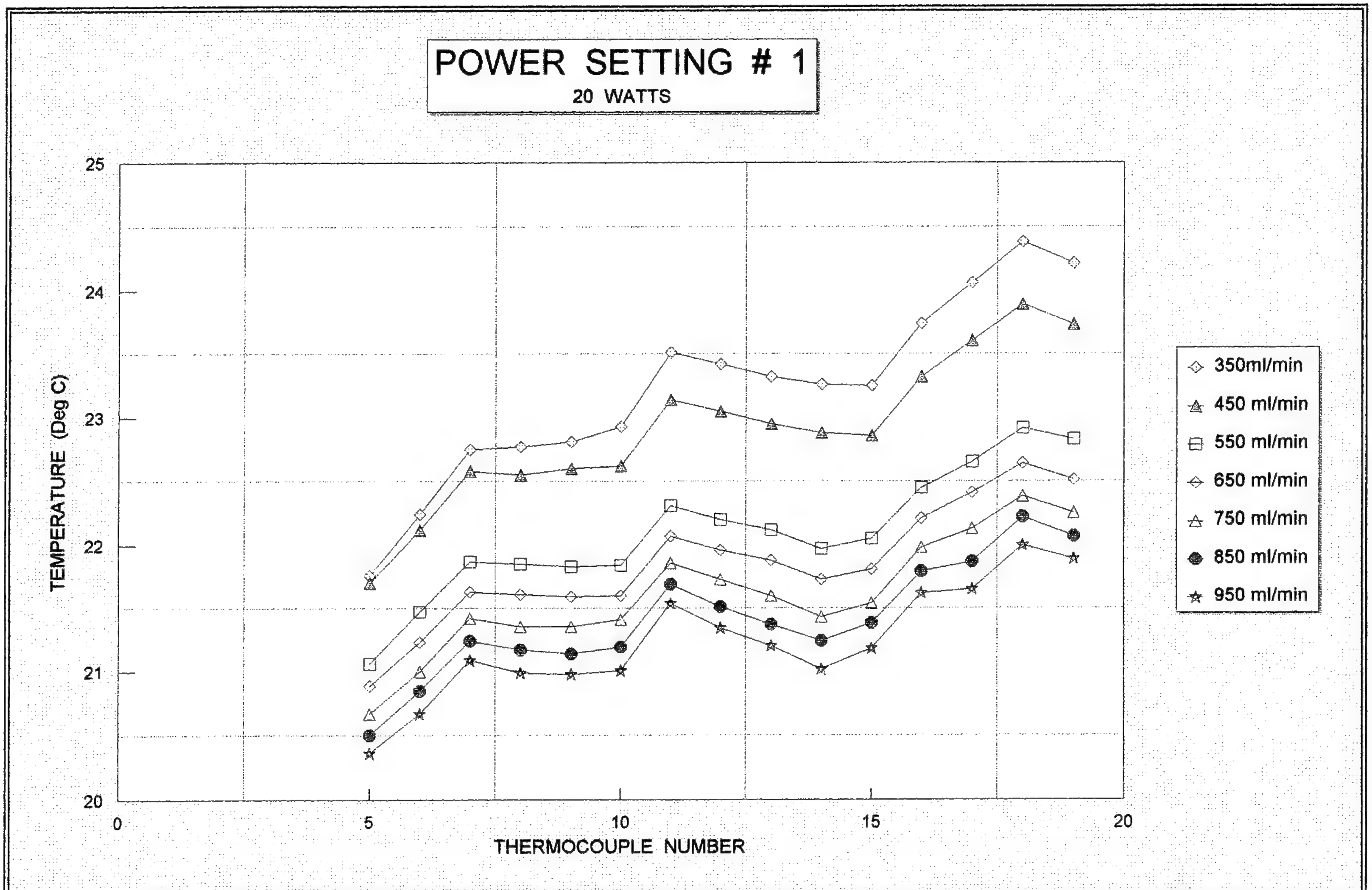


Figure 18. Temperature Distribution on the Module for Side -A at Power Setting 1.

FTM SIDE - A

POWER SETTING # 2 (30 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	3.38	3.381	3.383	3.381	3.382	3.382	3.382
Heater -2	3.363	3.365	3.366	3.364	3.365	3.365	3.365
Heater -3	3.338	3.339	3.34	3.339	3.339	3.339	3.34
Heater -4	3.253	3.254	3.255	3.254	3.254	3.254	3.255
Heater -5	3.329	3.33	3.332	3.33	3.331	3.331	3.331
Heater -6	3.356	3.358	3.359	3.358	3.358	3.358	3.359
Heater -7	3.333	3.334	3.335	3.334	3.334	3.335	3.335
Heater -8	3.334	3.336	3.337	3.336	3.336	3.336	3.337
Heater -9	3.38	3.381	3.382	3.381	3.381	3.382	3.382
TOT. POW.	**30.066**	**30.078**	**30.089**	**30.077**	**30.08**	**30.082**	**30.086**
Av. Sur. T.	23.33	22.93	22.69	22.45	22.3	22.17	22.07
T in	20.47	20.44	20.49	20.43	20.44	20.39	20.41
T out	23.54	22.92	22.56	22.19	22.01	21.79	21.69
DENSITY	0.7927	0.793	0.7931	0.7933	0.7933	0.7934	0.7935
SP.HEAT	2.0617	2.0602	2.0595	2.0586	2.0582	2.0576	2.0574
Q fluid	29.27	30.39	30.99	31.14	32.04	32.38	33.09
Q ins	0.06	0.04	0.02	0.01	0	-0.01	-0.02
Q total	**29.33**	**30.43**	**31.01**	**31.15**	**32.04**	**32.37**	**33.07**
DELTA Q	-0.736	0.352	0.921	1.073	1.96	2.288	2.984
DT ins	1.22	0.82	0.53	0.2	0.01	-0.22	-0.38
DT fluid	3.12	2.43	2.06	1.83	1.55	1.47	1.26

THERMOCOUPLE READINGS

T/C -0	22.11	22.11	22.16	22.25	22.29	22.39	22.45
T/C -1	22.3	22.04	21.96	21.85	21.77	21.73	21.66
T/C -2	19.74	19.62	19.82	19.75	19.85	19.77	19.86
T/C -3	20.5	20.55	20.58	20.48	20.53	20.47	20.54
T/C -4	23.62	22.98	22.64	22.31	22.08	21.94	21.8
T/C -5	21.27	21.19	21.16	21.03	21	20.92	20.94
T/C -6	21.93	21.8	21.66	21.55	21.46	21.43	21.34
T/C -7	22.61	22.4	22.27	22.08	21.99	21.87	21.86
T/C -8	22.69	22.42	22.25	22.04	21.93	21.83	21.77
T/C -9	23.12	22.8	22.63	22.47	22.33	22.25	22.16
T/C -10	22.84	22.47	22.27	22.06	21.91	21.79	21.73
T/C -11	23.73	23.34	23.08	22.87	22.7	22.57	22.44
T/C -12	23.59	23.15	22.83	22.59	22.4	22.27	22.18
T/C -13	23.44	22.94	22.68	22.39	22.22	22.09	21.94
T/C -14	23.42	22.93	22.62	22.33	22.15	21.98	21.87
T/C -15	23.28	22.79	22.56	22.29	22.15	21.99	21.88
T/C -16	23.98	23.48	23.19	22.95	22.76	22.63	22.51
T/C -17	24.6	23.95	23.6	23.24	23	22.8	22.7
T/C -18	24.87	24.23	23.89	23.56	23.34	23.14	23
T/C -19	24.63	23.99	23.66	23.32	23.1	22.95	22.76

Table 7. Power and Temperature Data for Side-A at Power Setting 2.

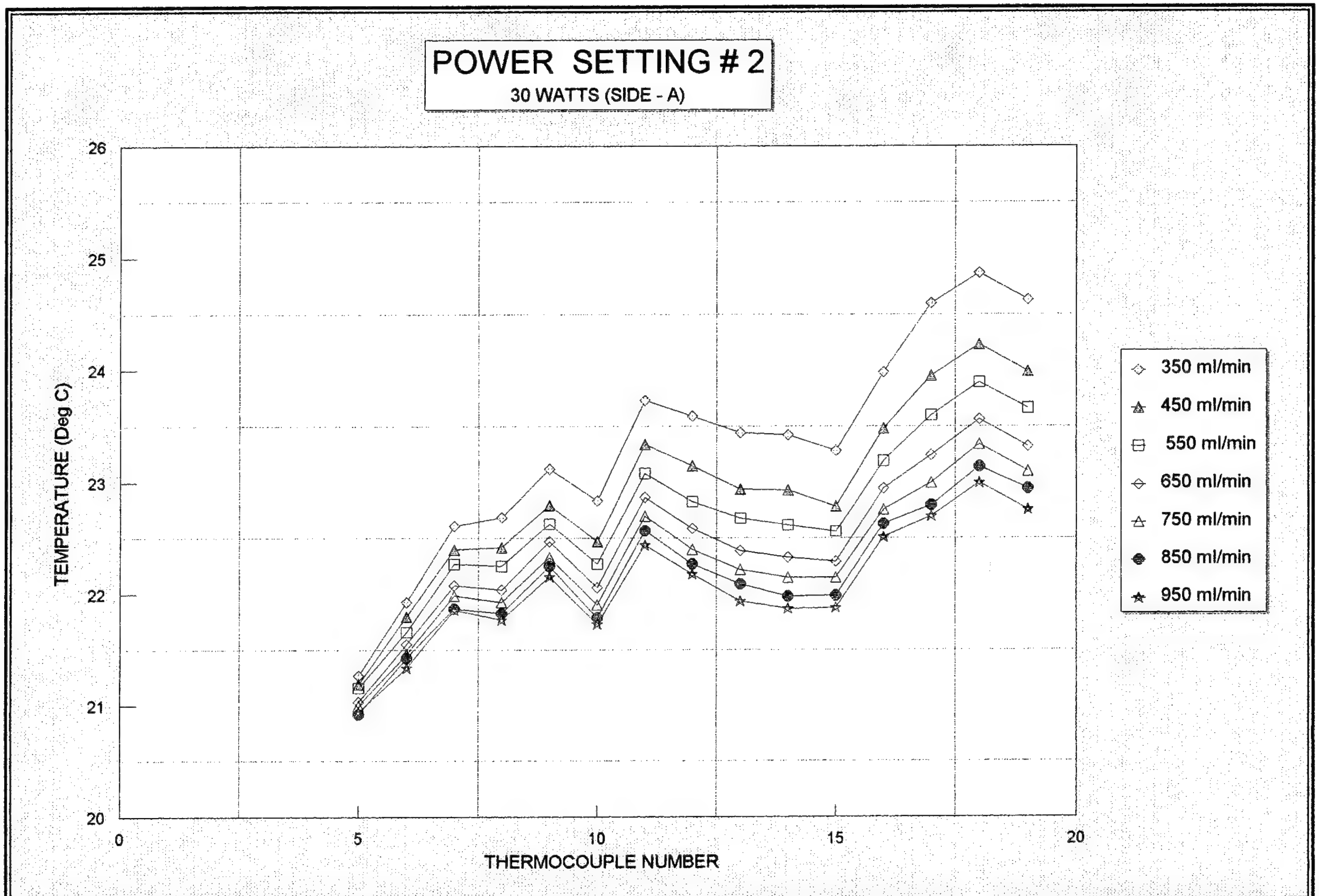


Figure 19. Temperature Distribution on the Module for Side - A, at Power Setting 2.

FTM SIDE - A

POWER SETTING # 3 (40 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	4.5	4.503	4.506	4.508	4.509	4.511	4.511
Heater -2	4.477	4.48	4.483	4.486	4.487	4.488	4.489
Heater -3	4.443	4.446	4.449	4.452	4.453	4.454	4.455
Heater -4	4.326	4.329	4.332	4.335	4.336	4.338	4.34
Heater -5	4.432	4.434	4.438	4.44	4.441	4.442	4.443
Heater -6	4.468	4.471	4.474	4.476	4.477	4.479	4.48
Heater -7	4.436	4.438	4.442	4.444	4.445	4.446	4.447
Heater -8	4.438	4.441	4.444	4.446	4.447	4.449	4.45
Heater -9	4.498	4.501	4.504	4.507	4.508	4.509	4.51
TOT. POW.	**40.018**	**40.043**	**40.072**	**40.094**	**40.103**	**40.116**	**40.125**
Av. Sur. T.	24.96	24.04	23.6	23.31	23.08	22.91	22.73
T in	21.09	20.76	20.66	20.61	20.64	20.59	20.63
T out	25.26	24.01	23.41	22.97	22.68	22.43	22.26
DENSITY	0.7917	0.7924	0.7927	0.7929	0.793	0.7931	0.7931
SP.HEAT	2.0669	2.0634	2.0618	2.0607	2.0601	2.0595	2.0592
Q fluid	39.8	39.85	41.2	41.77	41.66	42.58	42.15
Q ins	0.03	-0.01	-0.02	-0.02	-0.03	-0.03	-0.03
Q total	**39.83**	**39.84**	**41.18**	**41.75**	**41.63**	**42.55**	**42.12**
DELTA Q	-0.188	-0.203	1.108	1.656	1.527	2.434	1.995
DT ins	0.71	-0.18	-0.39	-0.43	-0.58	-0.62	-0.76
DT fluid	4.2	3.23	2.77	2.33	2.01	1.81	1.66

THERMOCOUPLE READINGS

T/C -0	24.25	24.22	23.99	23.74	23.66	23.53	23.49
T/C -1	24.76	24.02	23.54	23.18	22.99	22.83	22.7
T/C -2	19.82	19.9	19.78	19.8	20.05	19.87	19.94
T/C -3	21.15	20.86	20.73	20.74	20.73	20.7	20.65
T/C -4	25.35	24.09	23.5	23.07	22.74	22.51	22.31
T/C -5	22.18	21.7	21.52	21.45	21.32	21.27	21.16
T/C -6	23.06	22.5	22.21	22.08	21.95	21.85	21.72
T/C -7	24.01	23.33	23.04	22.85	22.72	22.55	22.4
T/C -8	24.13	23.31	22.97	22.77	22.59	22.44	22.31
T/C -9	24.27	23.45	23.11	23.15	23.1	23	22.83
T/C -10	24.4	23.49	23.07	22.76	22.56	22.37	22.2
T/C -11	25.5	24.64	24.14	23.83	23.57	23.42	23.26
T/C -12	25.35	24.35	23.84	23.5	23.23	23.05	22.85
T/C -13	25.11	24.1	23.6	23.24	22.99	22.77	22.6
T/C -14	25.08	24	23.49	23.13	22.88	22.67	22.44
T/C -15	24.83	23.88	23.4	23.07	22.83	22.64	22.47
T/C -16	25.95	24.94	24.43	24.03	23.75	23.53	23.35
T/C -17	26.66	25.42	24.83	24.36	24.04	23.77	23.53
T/C -18	27.06	25.86	25.27	24.84	24.51	24.28	24.04
T/C -19	26.79	25.6	25.03	24.55	24.23	24	23.77

Table 8. Power and Temperature Data for Side-A at Power Setting 3.

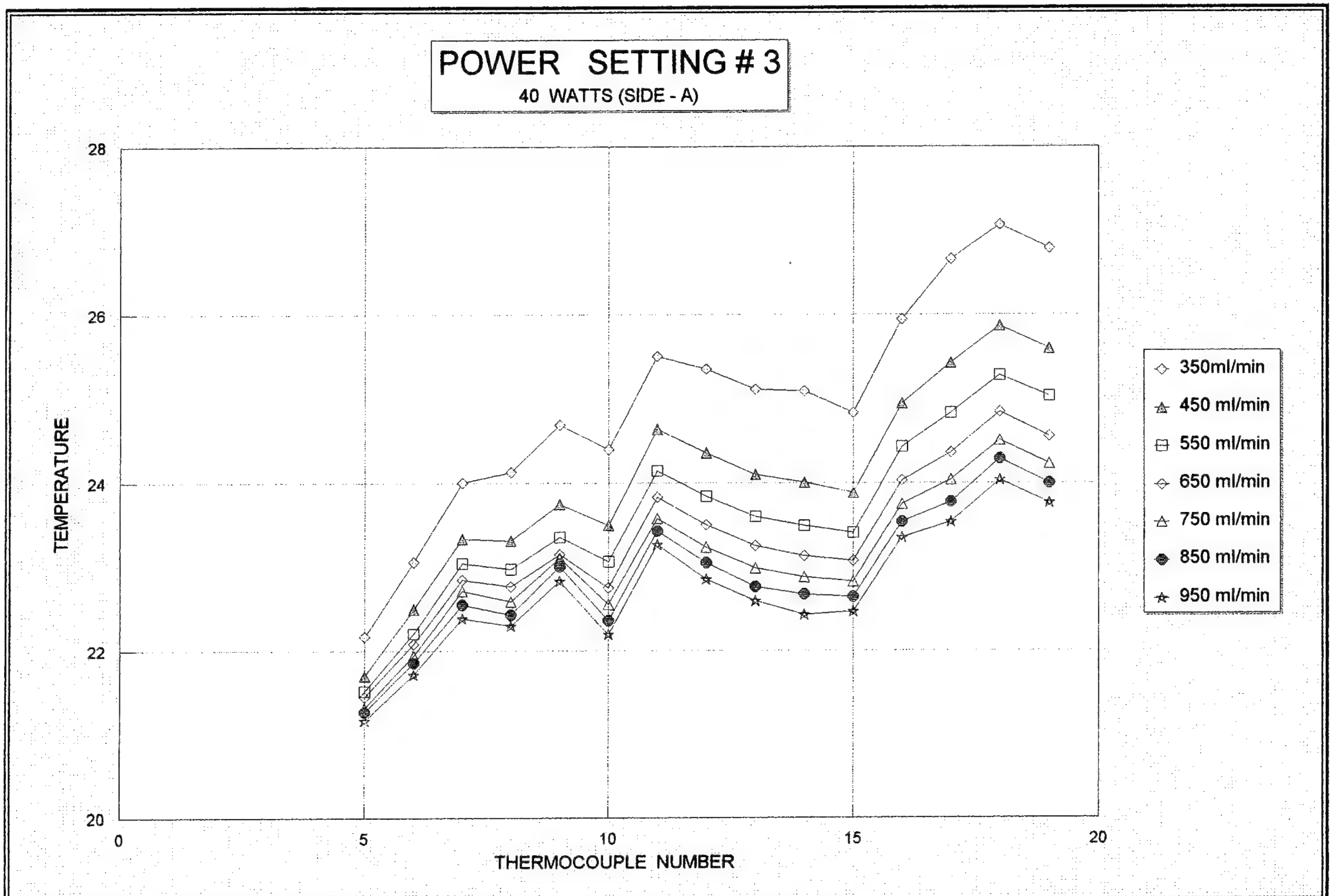


Figure 20. Temperature Distribution on the Module for Side -A , at Power Setting 3

FTM SIDE - A

POWER SETTING # 4 (50 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	5.632	5.632	5.624	5.625	5.626	5.627	5.628
Heater -2	5.603	5.604	5.596	5.597	5.599	5.599	5.6
Heater -3	5.56	5.561	5.554	5.555	5.556	5.557	5.557
Heater -4	5.415	5.416	5.409	5.41	5.411	5.412	5.413
Heater -5	5.546	5.547	5.539	5.541	5.542	5.543	5.543
Heater -6	5.591	5.592	5.584	5.585	5.587	5.588	5.588
Heater -7	5.55	5.551	5.543	5.544	5.545	5.546	5.546
Heater -8	5.553	5.554	5.546	5.547	5.549	5.549	5.55
Heater -9	5.628	5.629	5.622	5.623	5.624	5.625	5.626
TOT. POW	**50.078**	**50.086**	**50.017**	**50.027**	**50.039**	**50.046**	**50.051**
Av. Sur. T.	25.3	24.53	24.11	23.78	23.58	23.34	23.16
T in	20.65	20.61	20.65	20.63	20.7	20.57	20.62
T out	25.76	24.64	24.03	23.54	23.24	22.84	22.65
DENSITY	0.7917	0.7922	0.7924	0.7926	0.7927	0.7929	0.793
SP.HEAT	2.067	2.0644	2.0632	2.062	2.0615	2.0603	2.06
Q fluid	48.78	49.43	50.65	51.52	51.88	52.53	52.51
Q ins	0.12	0.08	0.06	0.04	0.03	0.02	0.01
Q total	**48.9**	**49.51**	**50.71**	**51.56**	**51.91**	**52.55**	**52.52**
DELTA Q	-1.178	-0.576	0.693	1.533	1.871	2.504	2.469
DT ins	2.67	1.77	1.3	0.95	0.75	0.5	0.29
DT fluid	5.16	4.08	3.31	2.86	2.48	2.33	2.09

THERMOCOUPLE READINGS

T/C -0	22.63	22.76	22.81	22.83	22.83	22.84	22.87
T/C -1	24.63	24.07	23.75	23.5	23.29	23.14	23
T/C -2	19.79	19.97	19.91	19.97	20.07	19.91	20.13
T/C -3	20.69	20.64	20.76	20.75	20.8	20.64	20.64
T/C -4	25.85	24.72	24.07	23.61	23.28	22.97	22.73
T/C -5	21.92	21.67	21.61	21.51	21.5	21.33	21.29
T/C -6	23.05	22.71	22.5	22.4	22.28	22.13	21.98
T/C -7	24.18	23.69	23.44	23.25	23.12	22.9	22.77
T/C -8	24.34	23.69	23.46	23.21	23.02	22.77	22.65
T/C -9	24.51	23.86	23.53	23.3	23.6	23.46	23.31
T/C -10	24.54	23.82	23.43	23.15	22.98	22.69	22.53
T/C -11	25.91	25.17	24.77	24.44	24.19	23.98	23.77
T/C -12	25.72	24.85	24.41	24.02	23.74	23.47	23.29
T/C -13	25.45	24.59	24.09	23.71	23.45	23.17	22.99
T/C -14	25.51	24.56	24.08	23.68	23.39	23.1	22.9
T/C -15	25.19	24.35	23.88	23.5	23.25	23.02	22.81
T/C -16	26.43	25.47	24.97	24.57	24.24	24.01	23.81
T/C -17	27.42	26.29	25.61	25.11	24.77	24.44	24.18
T/C -18	27.86	26.74	26.14	25.64	25.26	24.99	24.73
T/C -19	27.49	26.42	25.75	25.27	24.92	24.65	24.4

Table 9. Power and Temperature Data for Side-A at Power Setting 4.

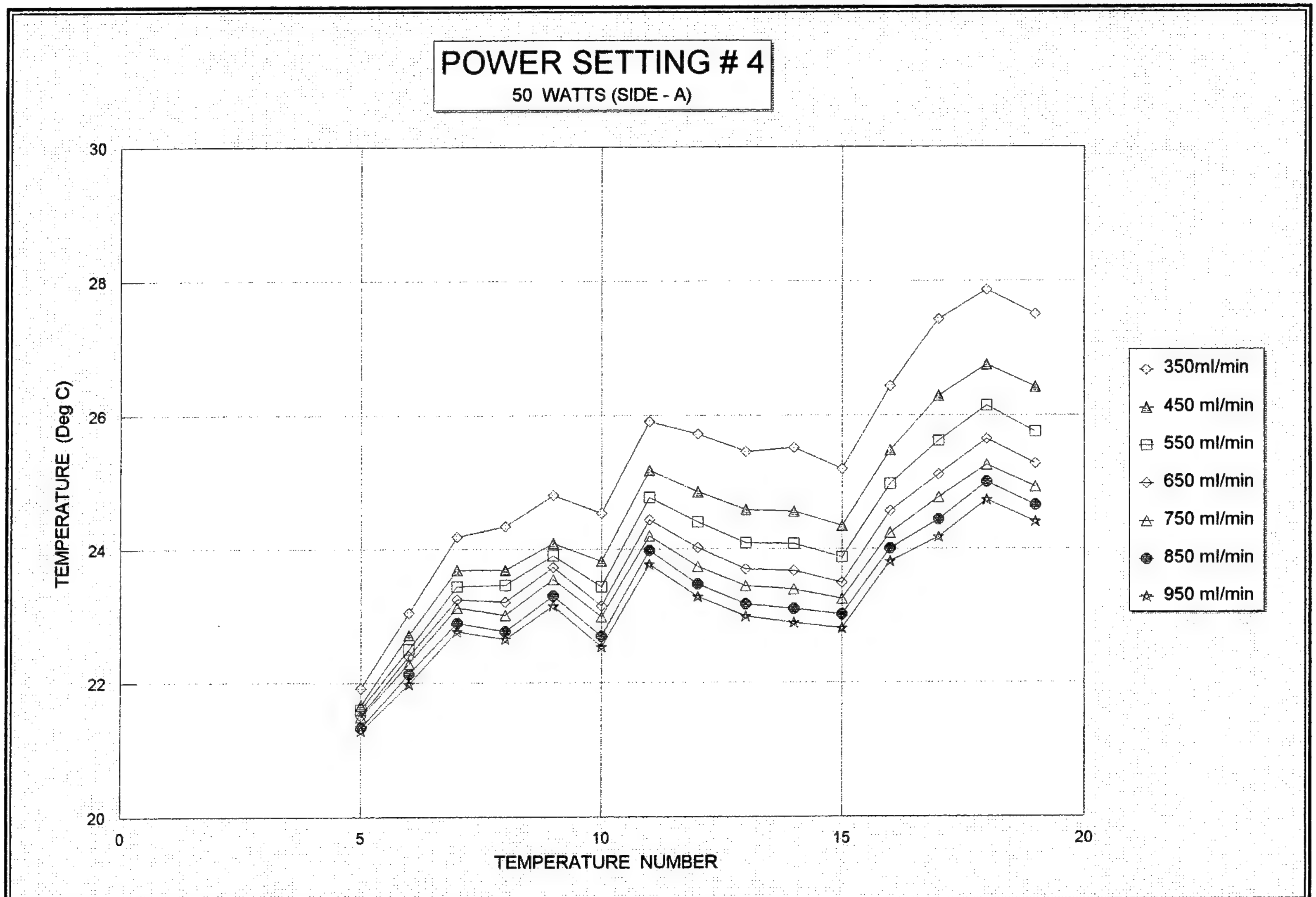


Figure 21. Temperature Distribution on the Module for Side - A, at Power Setting 4.

FTM SIDE - A

POWER SETTING # 5 (60 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	6.751	6.751	6.751	6.751	6.758	6.757	6.755
Heater -2	6.717	6.717	6.718	6.718	6.725	6.724	6.722
Heater -3	6.665	6.666	6.666	6.666	6.674	6.673	6.671
Heater -4	6.481	6.484	6.484	6.485	6.494	6.494	6.494
Heater -5	6.648	6.649	6.649	6.649	6.657	6.656	6.654
Heater -6	6.701	6.702	6.702	6.703	6.71	6.709	6.708
Heater -7	6.652	6.652	6.652	6.652	6.659	6.658	6.657
Heater -8	6.655	6.656	6.656	6.656	6.663	6.663	6.661
Heater -9	6.746	6.747	6.747	6.747	6.755	6.754	6.752
TOT. POW.	**60.016**	**60.024**	**60.025**	**60.027**	**60.095**	**60.088**	**60.074**
Av. Sur. T.	26.63	25.49	24.83	24.36	24.09	23.83	23.58
T in	21	20.77	20.66	20.61	20.64	20.6	20.56
T out	27.15	25.61	24.7	24.08	23.69	23.31	23
DENSITY	0.791	0.7917	0.7921	0.7924	0.7926	0.7927	0.7929
SP.HEAT	2.0709	2.0669	2.0647	2.0632	2.0624	2.0614	2.0607
Q fluid	58.77	59.4	60.57	61.46	62.32	62.73	63.12
Q ins	0.11	0.08	0.06	0.05	0.04	0.04	0.04
Q total	**58.88**	**59.48**	**60.63**	**61.51**	**62.36**	**62.77**	**63.16**
DELTA Q	-1.136	-0.544	0.605	1.483	2.265	2.682	3.086
DT ins	2.5	1.78	1.21	1.03	0.9	0.83	0.85
DT fluid	6.1	4.78	4.14	3.46	3	2.7	2.38

THERMOCOUPLE READINGS

T/C -0	24.13	23.71	23.62	23.33	23.19	23	22.73
T/C -1	24.52	23.78	23.45	23.16	22.94	22.76	22.56
T/C -2	19.71	19.77	19.85	20.01	20.15	20.01	20.01
T/C -3	21.1	20.87	20.66	20.66	20.73	20.69	20.66
T/C -4	27.2	25.65	24.8	24.12	23.73	23.39	23.04
T/C -5	22.62	22.08	21.79	21.62	21.55	21.52	21.41
T/C -6	23.93	23.27	22.89	22.61	22.51	22.39	22.26
T/C -7	25.23	24.48	24	23.66	23.51	23.34	23.13
T/C -8	25.44	24.52	23.96	23.61	23.37	23.19	23.01
T/C -9	26.25	25.35	24.83	24.43	24.24	24.03	23.78
T/C -10	25.68	24.63	23.99	23.53	23.31	23.07	22.86
T/C -11	27.41	26.26	25.6	25.11	24.85	24.59	24.31
T/C -12	27.11	25.84	25.12	24.6	24.3	24.02	23.73
T/C -13	26.78	25.49	24.8	24.23	23.93	23.61	23.33
T/C -14	26.76	25.51	24.71	24.19	23.85	23.55	23.25
T/C -15	26.47	25.22	24.53	24.02	23.72	23.44	23.2
T/C -16	27.91	26.57	25.84	25.3	24.95	24.67	24.33
T/C -17	29.07	27.51	26.59	25.94	25.54	25.14	24.81
T/C -18	29.58	28.01	27.13	26.49	26.08	25.67	25.32
T/C -19	29.19	27.57	26.71	26.08	25.67	25.28	24.97

Table 10. Power and Temperature Data for Side-A at Power Setting 5.

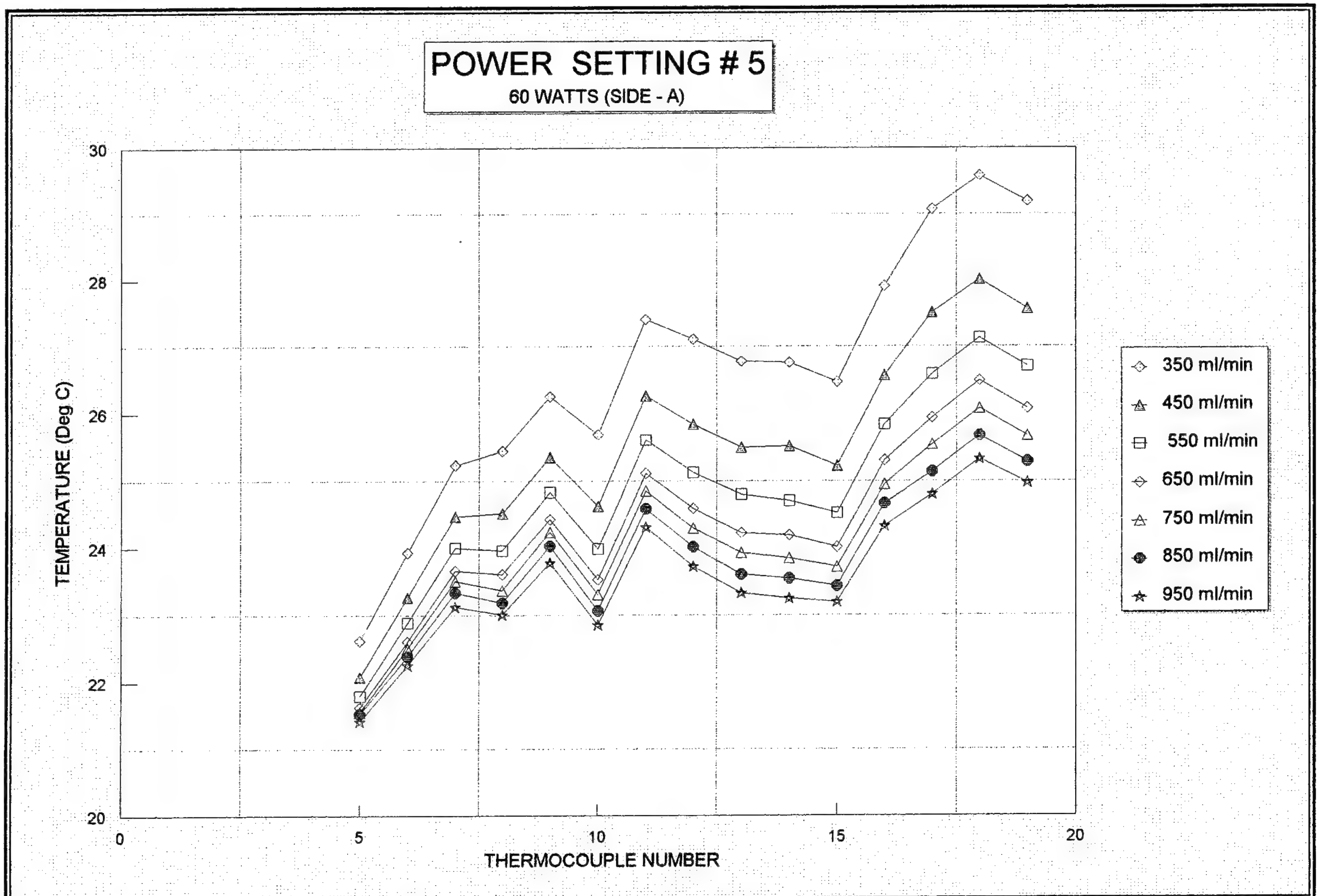


Figure 22. Temperature Distribution on the Module for Side -A, at Power Setting 5.

FTM SIDE - A

POWER SETTING # 6 (70 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	7.888	7.88	7.881	7.884	7.883	7.884	7.875
Heater -2	7.847	7.84	7.842	7.843	7.844	7.845	7.837
Heater -3	8.787	7.78	7.781	7.783	7.784	7.785	7.777
Heater -4	7.572	7.564	7.569	7.568	7.573	7.572	7.566
Heater -5	7.766	7.759	7.761	7.762	7.764	7.764	7.756
Heater -6	7.828	7.821	7.823	7.824	7.826	7.826	7.819
Heater -7	7.769	7.762	7.763	7.764	7.765	7.766	7.758
Heater -8	7.773	7.766	7.768	7.771	7.771	7.771	7.763
Heater -9	7.879	7.872	7.874	7.876	7.877	7.878	7.871
TOT. POW.	**71.109**	**70.044**	**70.062**	**70.075**	**70.087**	**70.091**	**70.022**
Av. Sur. T.	27.75	26.49	25.72	25.22	24.84	24.56	24.28
T in	21.12	20.88	20.84	20.83	20.8	20.81	20.74
T out	28.31	26.54	25.5	24.83	24.3	23.91	23.55
DENSITY	0.7904	0.7913	0.7917	0.792	0.7922	0.7924	0.7926
SP.HEAT	2.0737	2.0693	2.0669	2.0653	2.0641	2.0632	2.0623
Q fluid	68.74	69.51	69.9	70.88	71.54	71.8	72.73
Q ins	0.13	0.07	0.04	0.02	0.01	0	-0.01
Q total	**68.87**	**69.58**	**69.94**	**70.9**	**71.55**	**71.8**	**72.72**
DELTA Q	-2.239	-0.464	-0.122	0.825	1.463	1.709	2.698
DT ins	2.78	1.47	0.92	0.49	0.25	0.1	-0.14
DT fluid	7.16	5.63	4.72	4	3.54	3.09	2.75

THERMOCOUPLE READINGS

T/C -0	24.97	25.02	24.8	24.73	24.59	24.46	24.42
T/C -1	27.04	26.07	25.43	24.99	24.66	24.4	24.19
T/C -2	19.93	19.85	19.97	20.05	20	20.03	20
T/C -3	21.19	20.99	20.85	20.88	20.83	20.88	20.82
T/C -4	28.35	26.62	25.57	24.88	24.37	23.97	23.57
T/C -5	22.96	22.48	22.15	21.97	21.86	21.8	21.66
T/C -6	24.6	23.9	23.47	23.19	22.99	22.81	22.68
T/C -7	26.09	25.28	24.72	24.39	24.11	23.98	23.72
T/C -8	26.31	25.31	24.7	24.29	24.04	23.83	23.57
T/C -9	27.35	26.33	25.72	25.34	25	24.79	24.57
T/C -10	26.61	25.48	24.72	24.25	23.9	23.66	23.41
T/C -11	28.64	27.38	26.65	26.14	25.71	25.42	25.14
T/C -12	28.28	26.85	26.03	25.45	25.02	24.74	24.44
T/C -13	27.91	26.49	25.61	25.04	24.61	24.28	23.95
T/C -14	27.91	26.42	25.51	24.93	24.52	24.17	23.85
T/C -15	27.48	26.12	25.35	24.78	24.37	24.07	23.8
T/C -16	29.34	27.84	26.92	26.35	25.9	25.55	25.22
T/C -17	30.62	28.83	27.69	27.01	26.44	26.03	25.65
T/C -18	31.26	29.61	28.53	27.81	27.25	26.86	26.45
T/C -19	30.83	29.07	28.06	27.34	26.82	26.42	26.04

Table 11. Power and Temperature Data for Side-A at Power Setting 6.

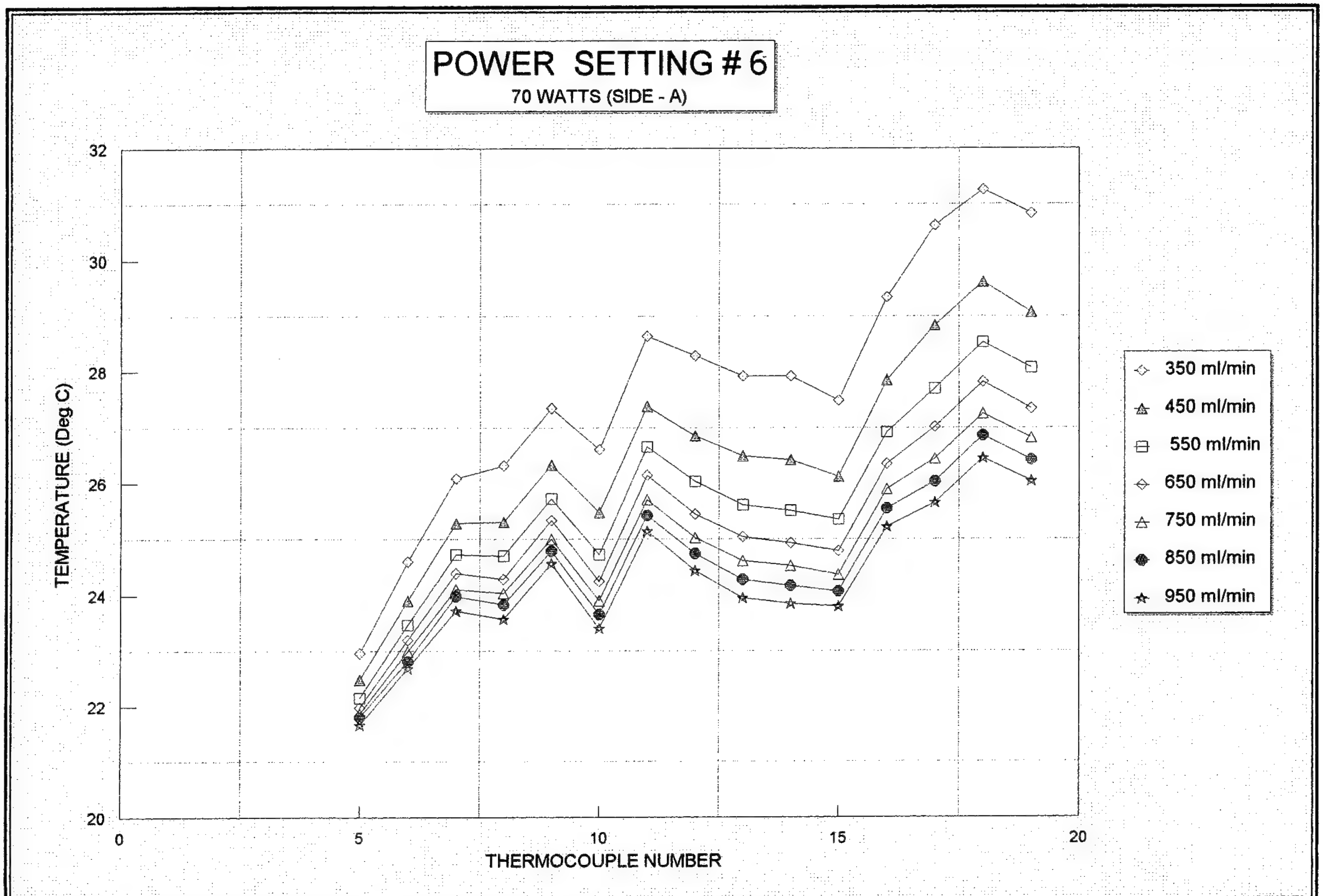


Figure 23. Temperature Distribution on the Module for Side -A, at Power Setting 6.

FTM SIDE - A

POWER SETTING # 7 (80 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	9.007	8.992	9.002	9.001	9.001	9.002	9.001
Heater -2	8.961	8.946	8.956	8.955	8.956	8.957	8.957
Heater -3	8.892	8.877	8.887	8.887	8.888	8.888	8.888
Heater -4	8.659	8.648	8.652	8.654	8.65	8.644	8.645
Heater -5	8.868	8.855	8.864	8.863	8.864	8.864	8.864
Heater -6	8.938	8.924	8.934	8.934	8.935	8.935	8.936
Heater -7	8.869	8.859	8.864	8.864	8.864	8.865	8.865
Heater -8	8.874	8.866	8.87	8.87	8.87	8.871	8.872
Heater -9	8.996	8.987	8.992	8.991	8.993	8.993	8.993
TOT. POW.	**80.064**	**79.954**	**80.021**	**80.019**	**80.021**	**80.019**	**80.021**
Av. Sur. T.	28.85	26.6	26.52	25.99	25.54	25.15	24.9
T in	21.31	20.99	20.97	20.97	20.85	20.92	20.83
T out	29.45	27.36	26.23	25.54	24.88	24.4	24.01
DENSITY	0.7899	0.7909	0.7914	0.7916	0.792	0.7921	0.7923
SP.HEAT	2.0767	2.0713	2.0688	2.0672	2.0655	2.0646	2.0635
Q fluid	77.89	78.26	78.94	81.02	82.41	80.62	82.32
Q ins	0.14	0.05	0.05	0.03	0.01	0	-0.01
Q total	**78.03**	**78.31**	**78.99**	**81.05**	**82.42**	**80.62**	**82.31**
DELTA Q	-2.034	-1.644	-1.031	1.031	2.399	0.601	2.289
DT ins	3.14	1.19	1.02	0.6	0.24	-0.09	-0.16
DT fluid	8.14	5.31	5.25	4.49	3.97	3.47	3.18

THERMOCOUPLE READINGS

T/C -0	25.71	25.41	25.5	25.39	25.3	25.24	25.06
T/C -1	28.02	26.22	26.16	25.7	25.31	25.05	24.8
T/C -2	19.99	19.96	20.04	20.06	19.97	20.12	19.93
T/C -3	21.4	21.13	21.03	21.03	21.04	20.94	20.91
T/C -4	29.54	26.44	26.28	25.52	25.01	24.41	24.09
T/C -5	23.45	22.53	22.56	22.25	22.13	21.99	21.86
T/C -6	25.26	24.02	23.94	23.63	23.41	23.22	23.04
T/C -7	27.02	25.45	25.41	25.07	24.76	24.48	24.23
T/C -8	27.18	25.44	25.39	24.92	24.62	24.3	24.05
T/C -9	28.4	26.57	26.58	26.08	25.76	25.4	25.27
T/C -10	27.51	25.47	25.35	24.86	24.46	24.12	23.91
T/C -11	29.88	27.59	27.55	26.96	26.53	26.2	25.94
T/C -12	29.42	26.94	26.82	26.3	25.76	25.28	25.04
T/C -13	29.01	26.46	26.36	25.79	25.23	24.86	24.54
T/C -14	29	26.38	26.31	25.71	25.18	24.72	24.43
T/C -15	28.53	26.19	26	25.51	25.04	24.6	24.35
T/C -16	30.69	28.01	27.93	27.32	26.76	26.28	26
T/C -17	32.08	28.89	28.76	28.03	27.34	26.83	26.44
T/C -18	32.94	29.82	29.67	28.91	28.32	27.79	27.44
T/C -19	32.34	29.23	29.14	28.44	27.76	27.25	26.95

Table 12. Power and Temperature Data for Side-A at Power Setting 7.

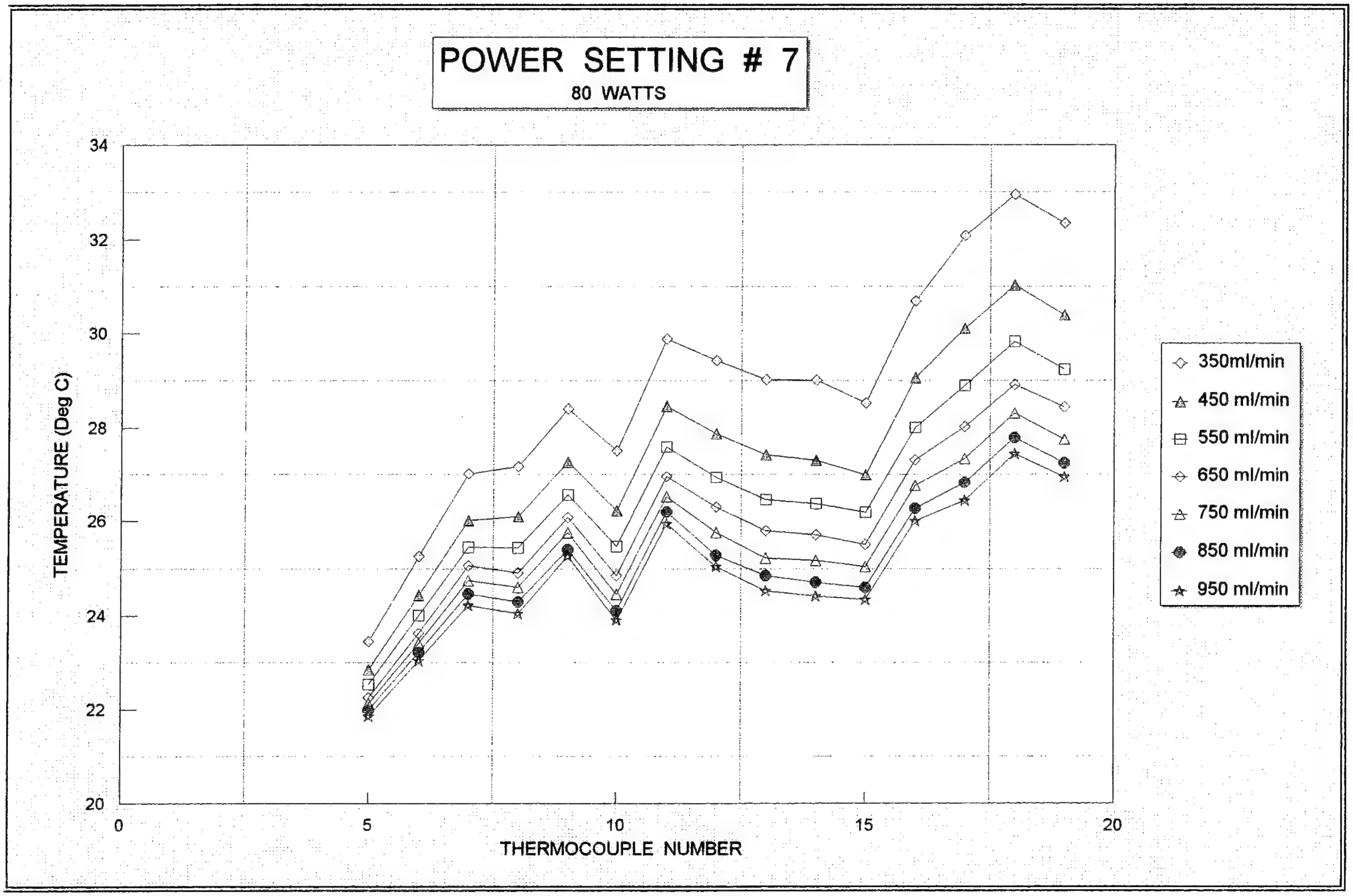


Figure 24. Temperature Distribution on the Module for Side - A, at Power Setting7.

FTM SIDE - A

POWER SETTING # 8 (90 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	10.125	10.123	10.125	10.127	10.107	10.121	10.124
Heater -2	10.073	10.071	10.074	10.078	10.057	10.071	10.075
Heater -3	9.994	9.993	9.996	10	9.98	9.993	9.997
Heater -4	9.792	9.789	9.791	9.793	9.774	9.787	9.79
Heater -5	9.969	9.968	9.97	9.973	9.954	9.968	9.972
Heater -6	10.046	10.045	10.049	10.053	10.033	10.047	10.051
Heater -7	9.968	9.966	9.969	9.971	9.952	9.966	9.968
Heater -8	9.975	9.973	9.976	9.979	9.959	9.974	9.977
Heater -9	10.11	10.109	10.112	10.117	10.096	10.11	10.114
TOT. POW.	**90.052**	**90.037**	**90.062**	**90.091**	**89.912**	**90.037**	**90.068**
Av. Sur. T.	29.38	27.78	26.9	26.23	25.65	25.17	24.82
T in	20.98	20.74	20.74	20.74	20.56	20.55	20.36
T out	30.14	27.92	26.68	25.78	25.01	24.41	23.84
DENSITY	0.7897	0.7907	0.7913	0.7916	0.792	0.7923	0.7926
SP.HEAT	2.0775	2.072	2.0693	2.0673	2.0651	2.0638	2.0621
Q fluid	87.66	88.22	89.16	89.35	90.98	89.42	90.06
Q ins	0.17	0.11	0.09	0.09	0.07	0.06	0.06
Q total	**87.83**	**88.33**	**89.25**	**89.44**	**91.05**	**89.48**	**90.12**
DELTA Q	-2.222	-1.707	-0.812	-0.651	1.138	-0.557	0.052
DT ins	3.76	2.48	1.97	1.87	1.58	1.37	1.23
DT fluid	9.18	7.18	5.99	5.04	4.43	3.88	3.54

THERMOCOUPLE READINGS

T/C -0	25.62	25.3	24.93	24.36	24.07	23.8	23.59
T/C -1	25.76	25.32	25.2	24.73	24.64	24.49	24.33
T/C -2	19.93	19.75	19.92	19.94	19.87	20.04	19.77
T/C -3	21.03	20.82	20.77	20.8	20.65	20.56	20.44
T/C -4	30.21	28	26.76	25.84	25.08	24.44	23.98
T/C -5	23.28	22.71	22.43	22.25	21.93	21.73	21.56
T/C -6	25.35	24.53	24.06	23.74	23.37	23.08	22.93
T/C -7	27.23	26.19	25.59	25.25	24.76	24.39	24.15
T/C -8	27.52	26.32	25.56	25.1	24.61	24.22	23.87
T/C -9	28.94	27.69	27.01	26.43	25.99	25.58	25.28
T/C -10	28	26.56	25.77	25.13	24.61	24.12	23.83
T/C -11	30.54	28.95	28.09	27.36	26.77	26.31	26.03
T/C -12	30.04	28.27	27.33	26.52	25.95	25.46	25.06
T/C -13	29.55	27.66	26.66	25.9	25.31	24.71	24.33
T/C -14	29.65	27.77	26.74	26.01	25.34	24.82	24.33
T/C -15	29.04	27.35	26.41	25.69	25.02	24.5	24.17
T/C -16	31.28	29.27	28.2	27.34	26.76	26.25	25.78
T/C -17	33.09	30.81	29.5	28.51	27.72	27.04	26.48
T/C -18	33.87	31.63	30.35	29.38	28.53	27.98	27.49
T/C -19	33.26	31.04	29.78	28.83	28.04	27.4	26.98

Table 13. Power and Temperature Data for Side -A, at Power Setting 8.

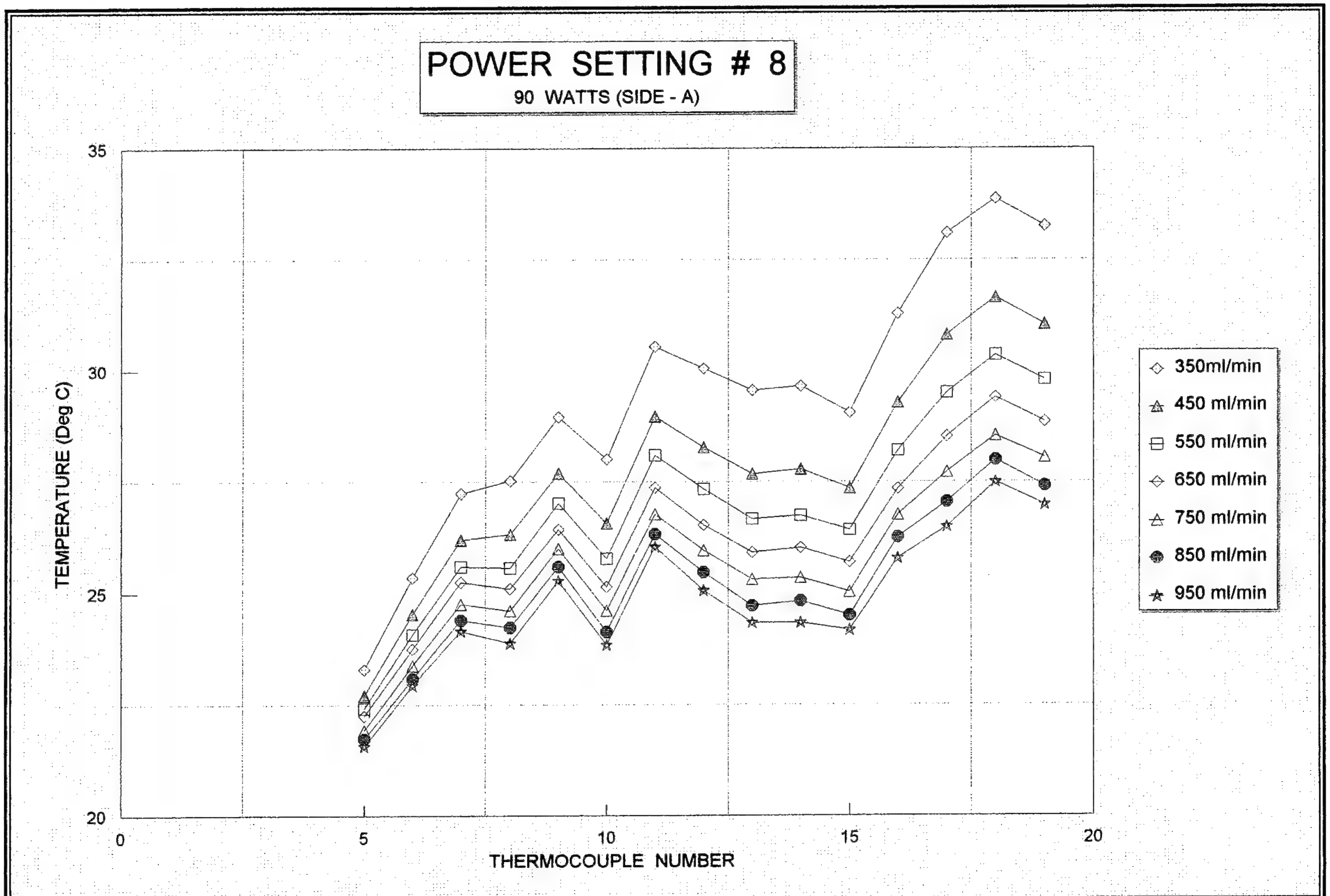


Figure 25. Temperature Distribution on the Module for Side -A, at Power Setting 8

FTM SIDE - A

POWER SETTING # 9 (100 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	11.254	11.257	11.244	11.246	11.248	11.248	11.247
Heater -2	11.196	11.202	11.189	11.191	11.192	11.192	11.19
Heater -3	11.109	11.114	11.102	11.104	11.105	11.105	11.104
Heater -4	10.819	10.824	10.855	10.849	10.849	10.85	10.846
Heater -5	11.082	11.087	11.074	11.077	11.078	11.078	11.077
Heater -6	11.166	11.172	11.16	11.163	11.164	11.165	11.163
Heater -7	11.078	11.082	11.069	11.071	11.072	11.072	11.07
Heater -8	11.085	11.09	11.078	11.08	11.081	11.081	11.081
Heater -9	11.236	11.242	11.23	11.232	11.234	11.234	11.232
TOT. POW.	**100.025**	**100.07**	**100.001**	**100.013**	**100.023**	**100.025**	**100.01**
Av. Sur. T.	30.16	28.48	27.46	26.88	26.35	25.95	25.56
T in	20.82	20.7	20.71	20.69	20.63	20.6	20.55
T out	31.03	28.61	27.19	26.34	25.56	25.05	24.5
DENSITY	0.7894	0.7905	0.7911	0.7914	0.7918	0.792	0.7923
SP.HEAT	2.0791	2.0735	2.0703	2.0684	2.0665	2.0653	2.064
Q fluid	97.75	97.24	97.29	100.19	100.83	103.12	102.27
Q ins	0.47	0.36	0.3	0.26	0.23	0.2	0.18
Q total	**98.22**	**97.6**	**97.59**	**100.45**	**101.06**	**103.32**	**102.45**
DELTA Q	-1.805	-2.47	-2.411	0.437	1.037	3.295	2.44
DT ins	5.89	4.04	3.04	2.58	2.1	1.74	1.45
DT fluid	10.21	7.91	6.48	5.65	4.93	4.45	3.95

THERMOCOUPLE READINGS

T/C -0	26.65	25.81	25.22	24.9	24.57	24.39	24.15
T/C -1	24.27	24.44	24.42	24.3	24.25	24.21	24.11
T/C -2	19.84	19.87	20.12	20	19.98	20.06	20.04
T/C -3	20.91	20.83	20.72	20.8	20.74	20.75	20.73
T/C -4	31.02	28.68	27.24	26.43	25.7	25.16	24.62
T/C -5	23.47	22.85	22.54	22.4	22.18	22.1	21.94
T/C -6	25.71	24.86	24.31	24.09	23.77	23.61	23.4
T/C -7	27.86	26.7	26.04	25.7	25.34	25.07	24.85
T/C -8	28.19	26.83	26.05	25.66	25.21	24.87	24.55
T/C -9	29.6	28.32	27.44	26.98	26.65	26.34	25.98
T/C -10	28.65	27.08	26.13	25.61	25.13	24.77	24.48
T/C -11	31.57	29.93	28.94	28.33	27.82	27.4	27.03
T/C -12	30.88	29.06	27.91	27.23	26.65	26.23	25.73
T/C -13	30.28	28.3	27.11	26.49	25.85	25.38	24.98
T/C -14	30.41	28.47	27.26	26.58	25.88	25.46	24.99
T/C -15	29.71	27.94	26.85	26.19	25.67	25.25	24.82
T/C -16	32.37	30.4	29.16	28.47	27.86	27.32	26.86
T/C -17	34.23	31.72	30.24	29.36	28.57	28.01	27.4
T/C -18	35.11	32.74	31.33	30.39	29.61	29.11	28.55
T/C -19	34.4	32	30.63	29.71	29.01	28.35	27.86

Table 14. Power and Temperature Data for Side-A, at Power Setting 9.

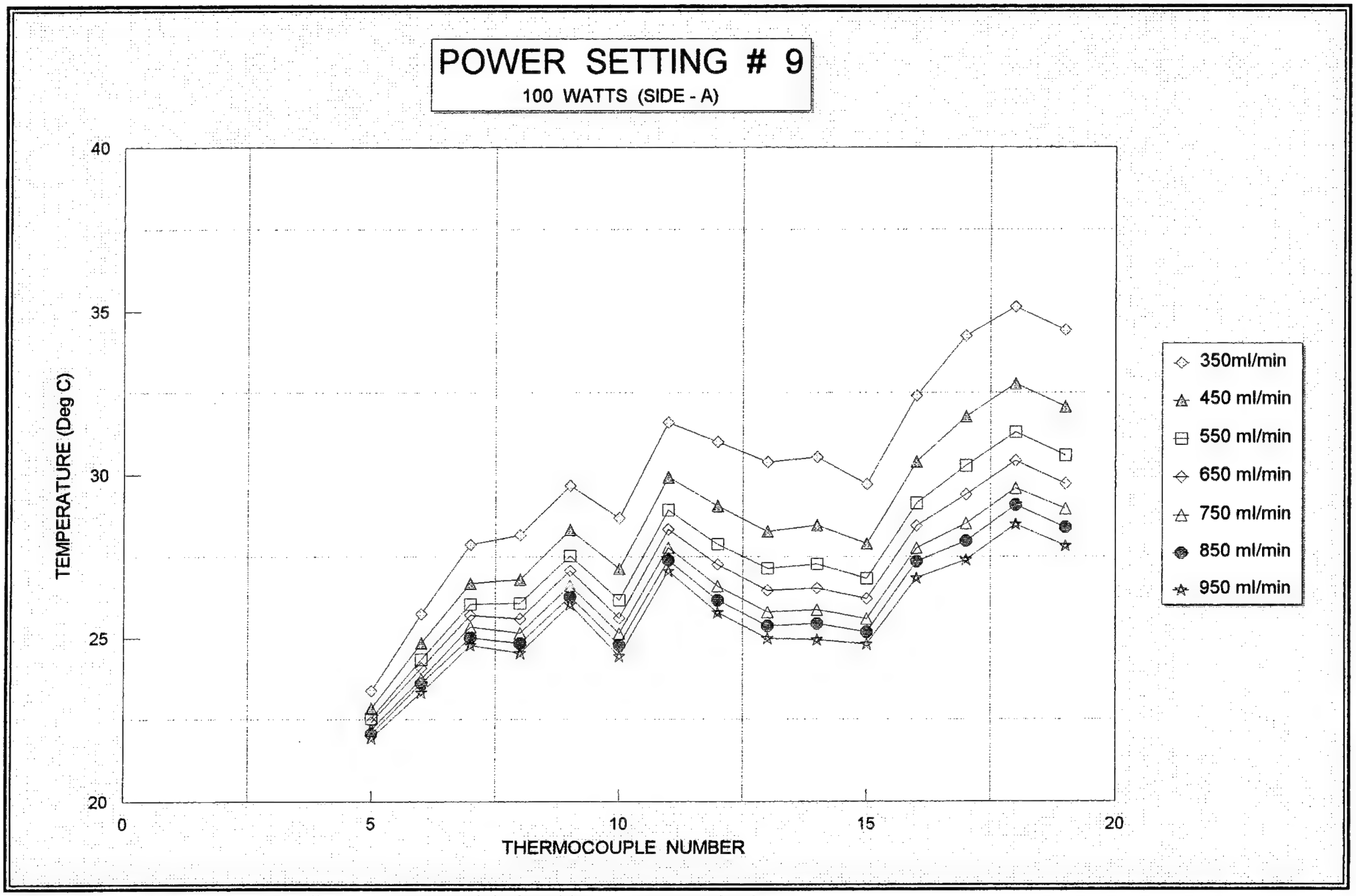


Figure 26. Temperature Distribution on the Module for Side - A, at Power Setting 9.

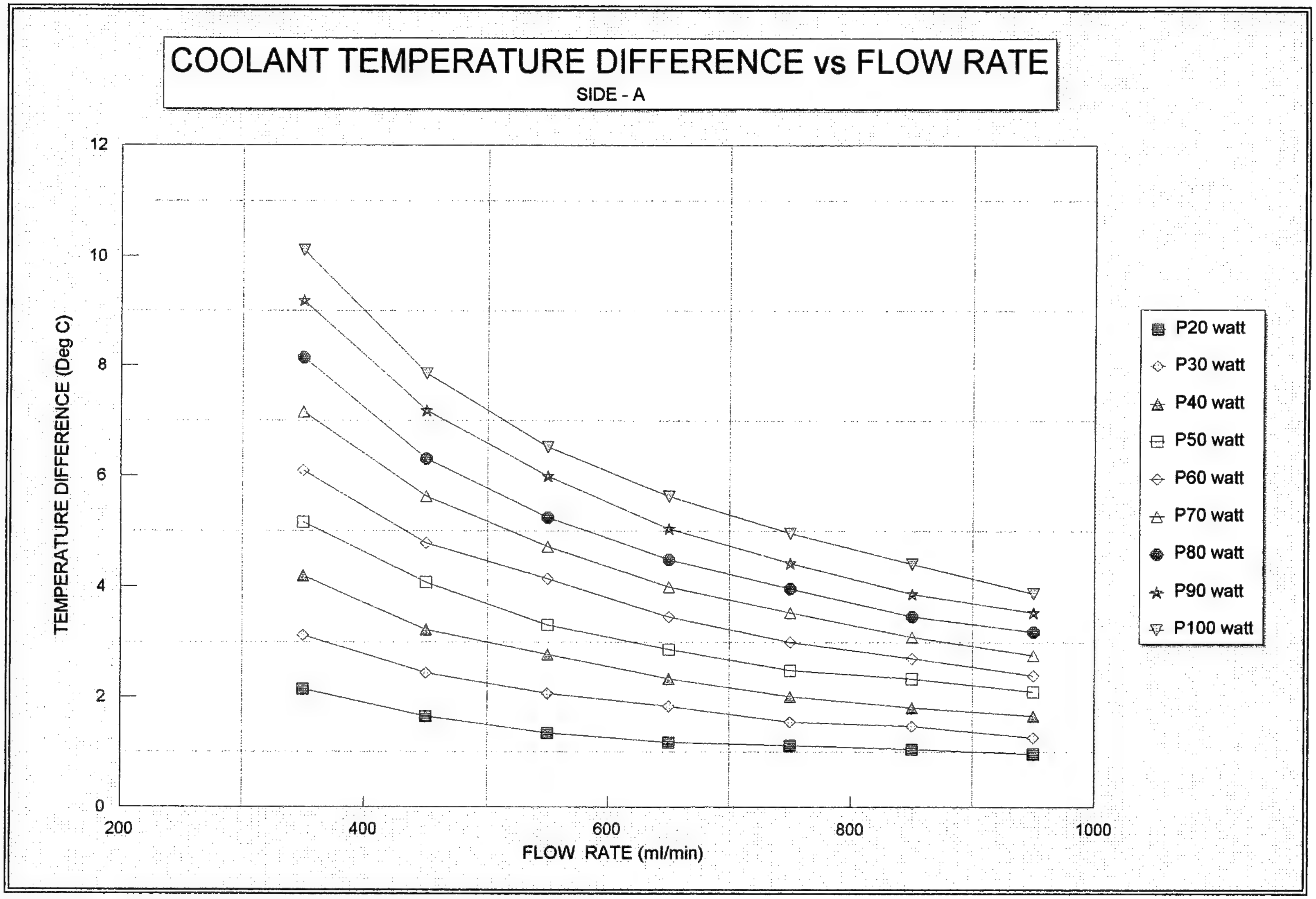


Figure 27. Coolant Temperature Difference vs Flow Rate for Side - A.

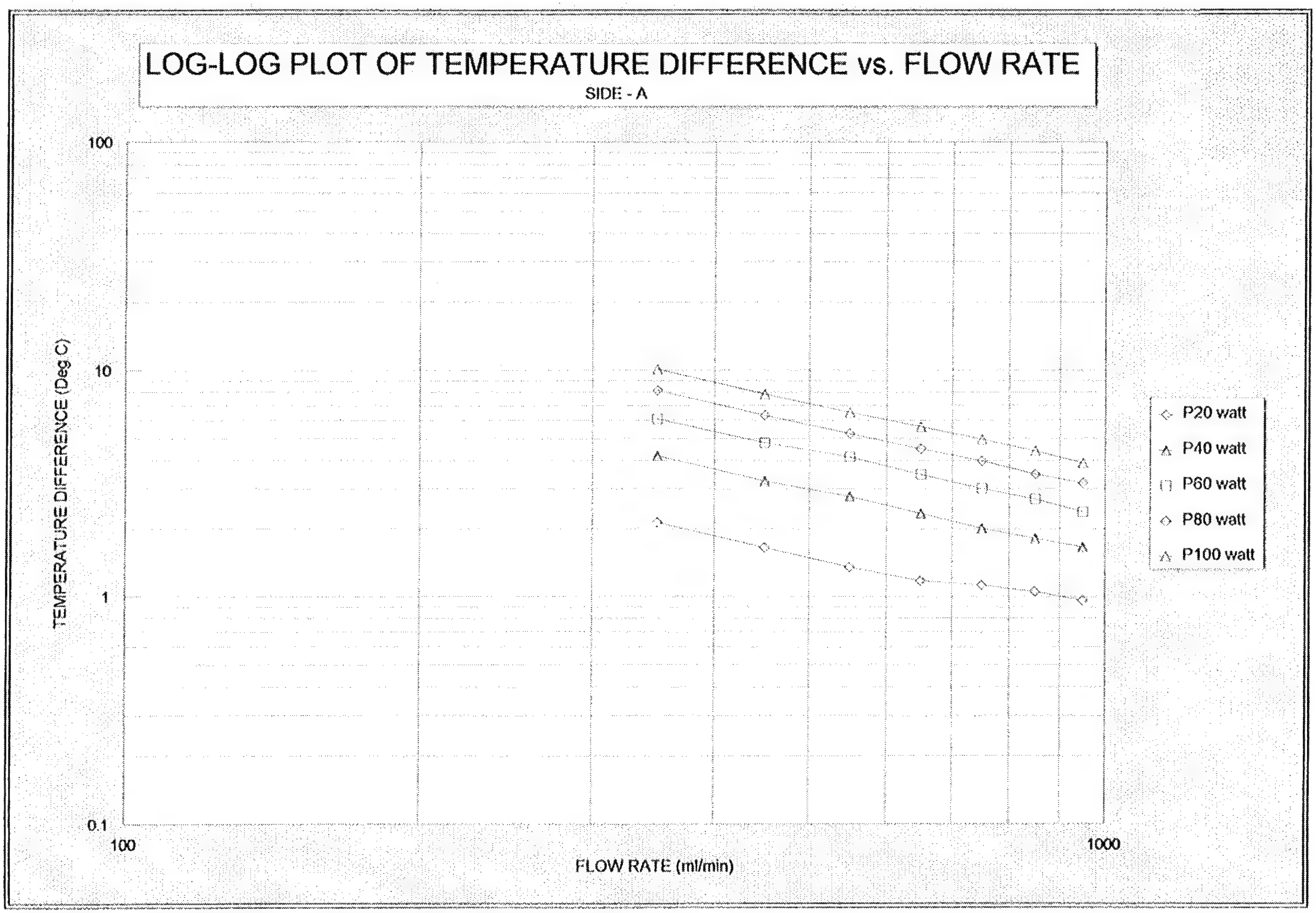


Figure 28-a Log-Log Plot of Temperature Difference vs.Flow Rtae for Side - A.

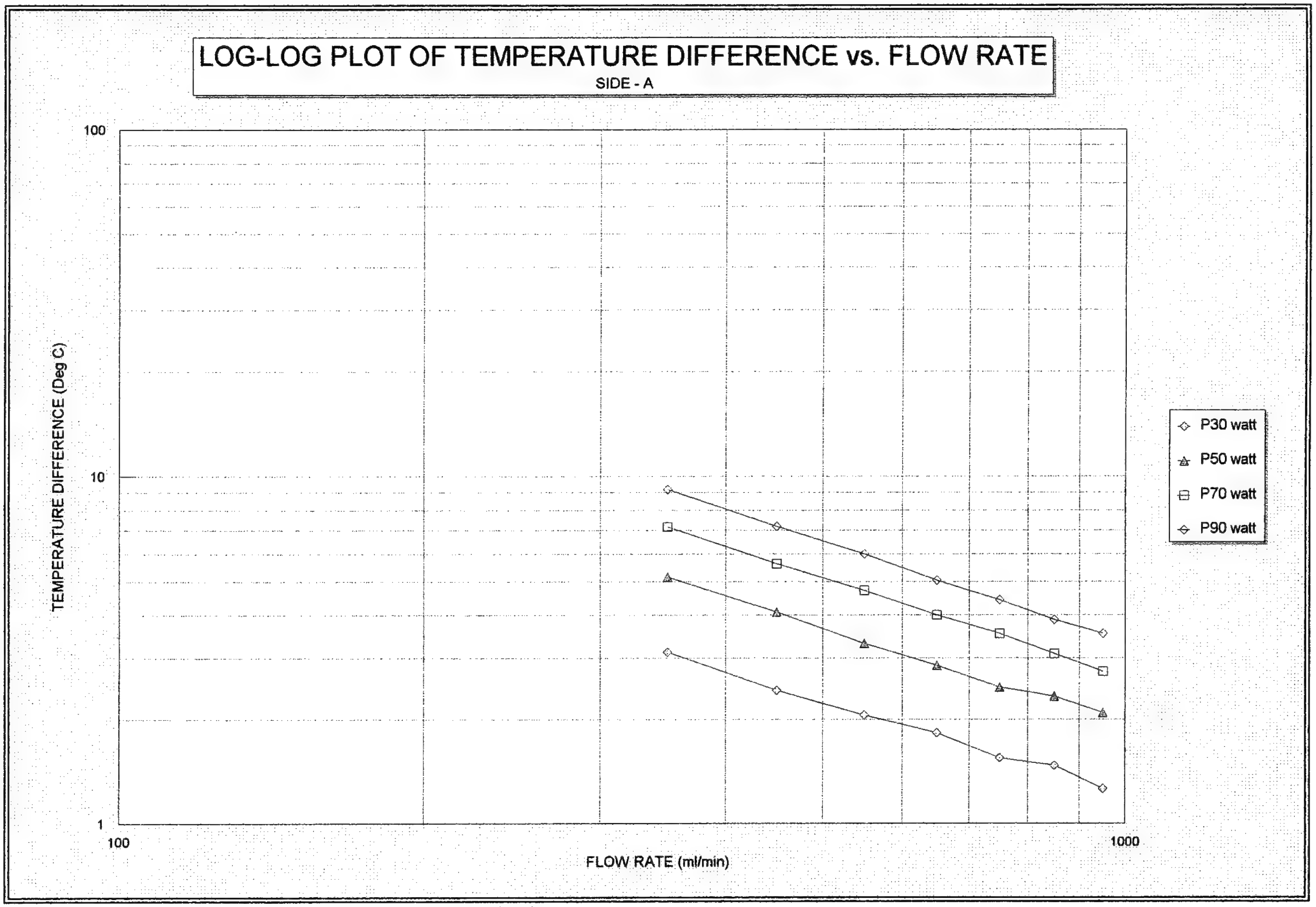


Figure 28-b Log-Log Plot of Temperature Difference vs.Flow Rtae for Side - A.

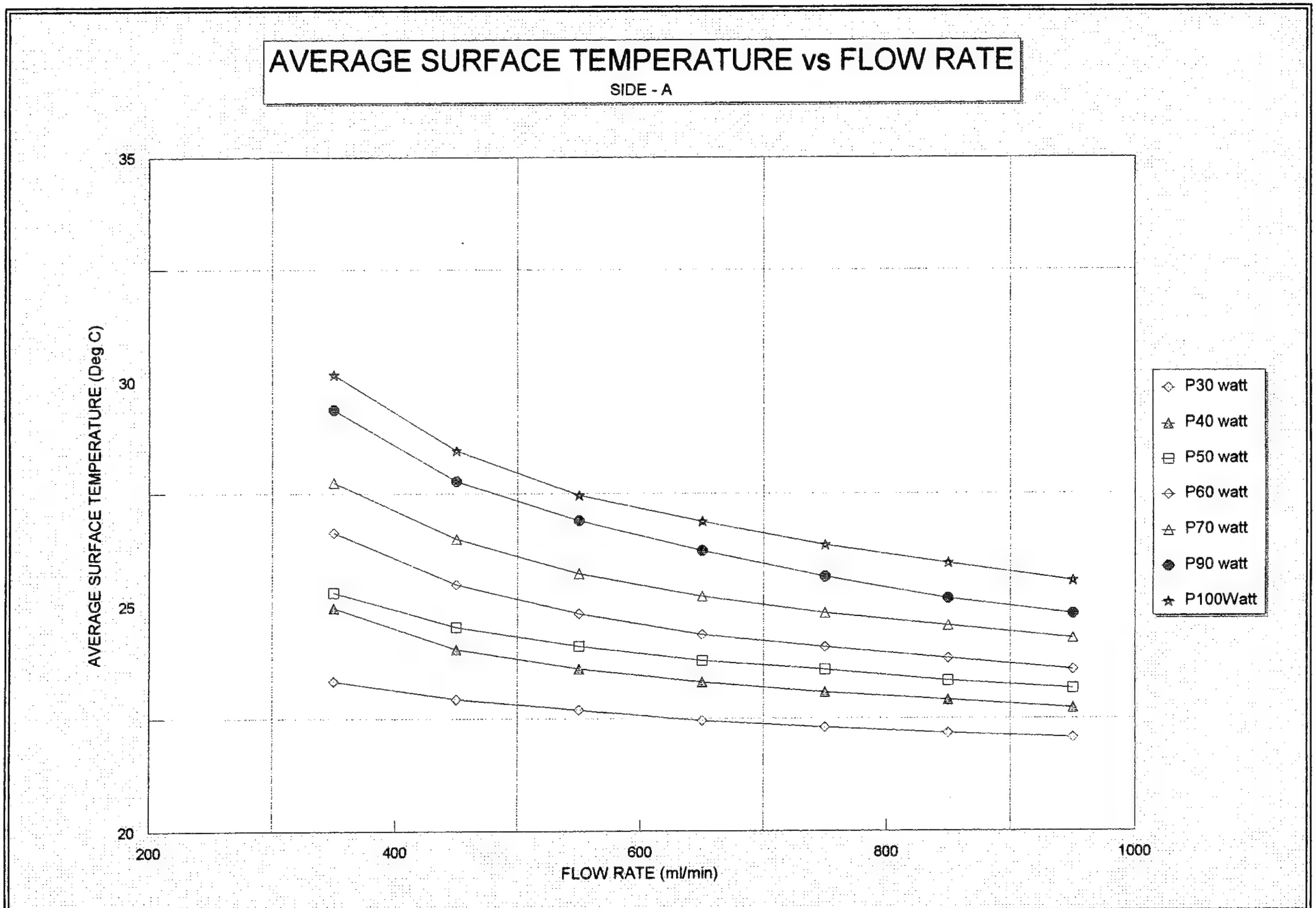


Figure 29. Average Surface Temperature vs Flow Rate for Side - A.

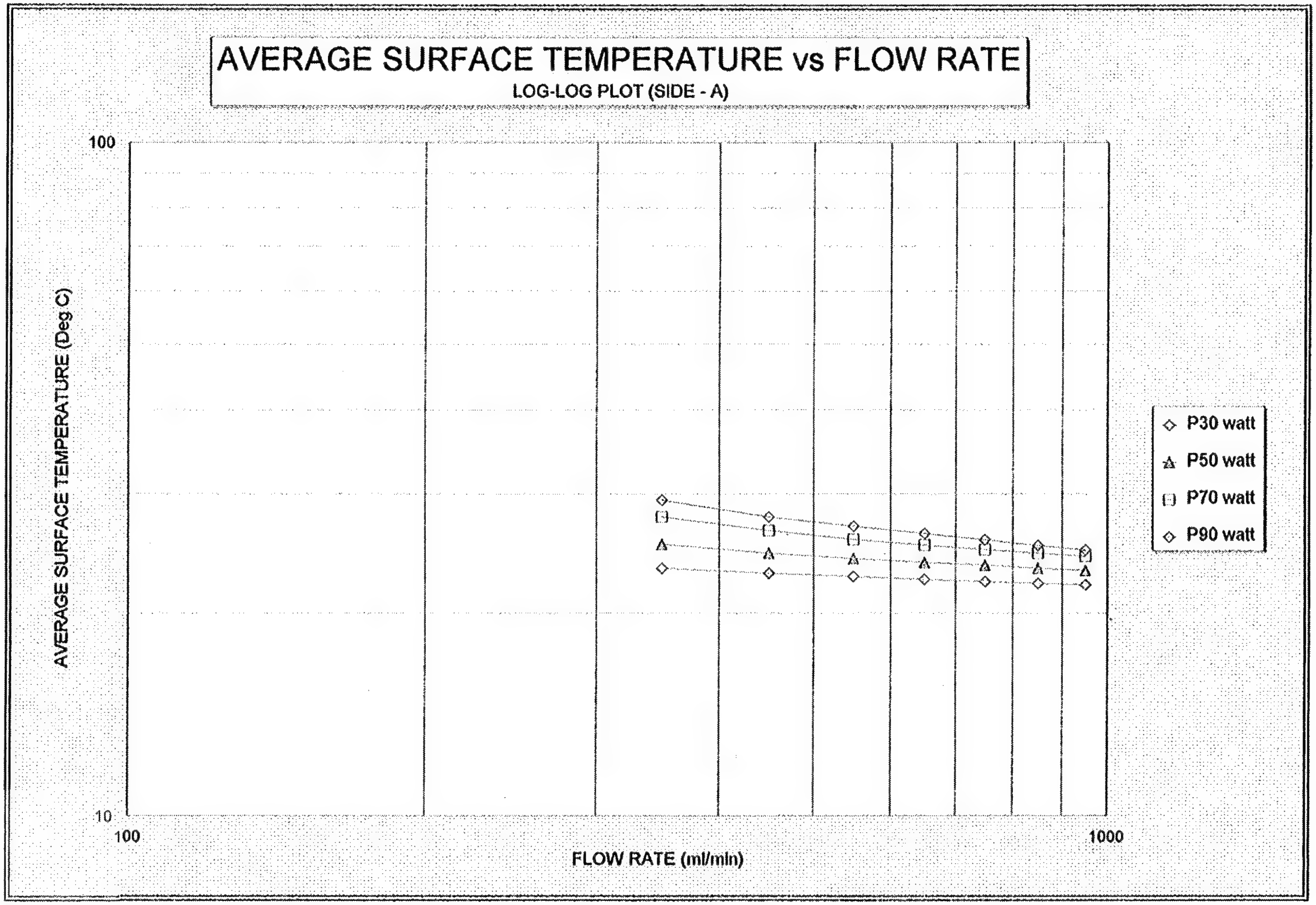


Figure 30. Log-Log Plot of Average Surface Temperature vs. Flow Rate for Side - A.

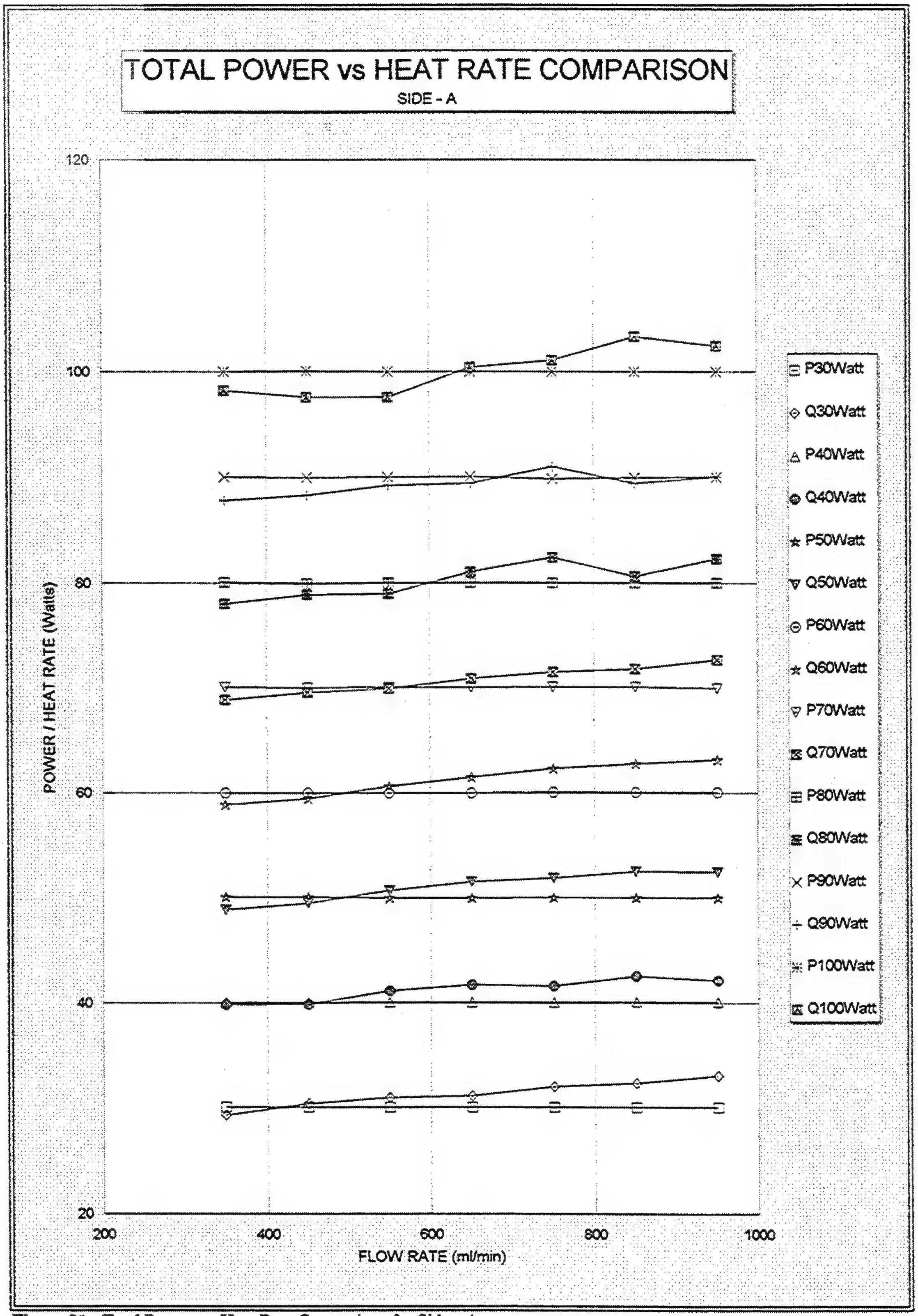


Figure 31. Total Power vs. Heat Rate Comparison for Side - A.

FTM SIDE - B

POWER SETTING # 1 (20 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	2.249	2.25	2.247	2.247	2.247	2.248	2.248
Heater -2	2.237	2.239	2.236	2.236	2.236	2.236	2.237
Heater -3	2.221	2.222	2.219	2.22	2.22	2.22	2.22
Heater -4	2.185	2.186	2.184	2.184	2.184	2.184	2.185
Heater -5	2.215	2.216	2.213	2.213	2.213	2.214	2.214
Heater -6	2.234	2.234	2.232	2.232	2.232	2.232	2.233
Heater -7	2.218	2.219	2.216	2.216	2.217	2.217	2.217
Heater -8	2.218	2.219	2.217	2.217	2.217	2.218	2.218
Heater -9	2.249	2.25	2.247	2.248	2.248	2.248	2.248
TOT. POW.	**20.026**	**20.035**	**20.011**	**20.013**	**20.014**	**20.017**	**20.02**
Av. Sur. T.	22.46	22.05	21.75	21.54	21.36	21.22	21.12
T in	20.92	20.81	20.7	20.59	20.52	20.5	20.41
T out	22.92	22.34	21.95	21.65	21.45	21.32	21.17
DENSITY	0.7928	0.793	0.7932	0.7934	0.7935	0.7936	0.7937
SP.HEAT	2.0613	2.0598	2.0587	2.0577	2.0571	2.0568	2.0563
Q fluid	19.07	18.74	18.71	18.75	18.98	18.96	19.64
Q ins	-0.06	-0.08	-0.08	-0.09	-0.09	-0.1	-0.1
Q total	**19.01**	**18.66**	**18.63**	**18.66**	**18.89**	**18.86**	**19.54**
DELTA Q	-1.016	-1.375	-1.381	-1.353	-1.124	-1.157	-0.48
DT ins	-1.34	-1.66	-1.78	-1.9	-1.98	-2.12	-2.15
DT fluid	1.94	1.51	1.26	1.04	1	0.85	0.77

THERMOCOUPLE READINGS

T/C -0	19.23	19.4	19.47	19.27	19.44	19.53	19.5
T/C -1	25.25	24.88	24.68	24.43	24.27	24.18	24.07
T/C -2	23.8	23.71	23.53	23.44	23.34	23.34	23.27
T/C -3	21.02	20.89	20.77	20.74	20.58	20.54	20.42
T/C -4	22.96	22.4	22.03	21.78	21.58	21.39	21.19
T/C -5	21.99	21.64	21.4	21.23	21.05	20.98	20.88
T/C -6	21.2	21	20.84	20.79	20.7	20.61	20.5
T/C -7	21.92	21.64	21.46	21.32	21.13	21	20.93
T/C -8	22.14	21.82	21.59	21.42	21.24	21.12	21.14
T/C -9	22.07	21.77	21.49	21.31	21.13	20.99	20.91
T/C -10	21.87	21.58	21.34	21.17	21	20.83	20.8
T/C -11	22.1	21.71	21.44	21.29	21.12	20.95	20.92
T/C -12	22.71	22.26	21.93	21.72	21.52	21.36	21.22
T/C -13	22.94	22.42	22.09	21.85	21.65	21.49	21.37
T/C -14	22.8	22.3	21.94	21.72	21.58	21.44	21.29
T/C -15	22.54	22.12	21.8	21.56	21.35	21.24	21.05
T/C -16	22.61	22.16	21.82	21.56	21.39	21.26	21.11
T/C -17	23.28	22.72	22.35	22.03	21.82	21.64	21.52
T/C -18	23.5	22.94	22.5	22.24	21.99	21.82	21.69
T/C -19	23.18	22.65	22.23	21.94	21.72	21.55	21.44

Table 15. Power and Temperature Data for Side - B at Power Setting 1.

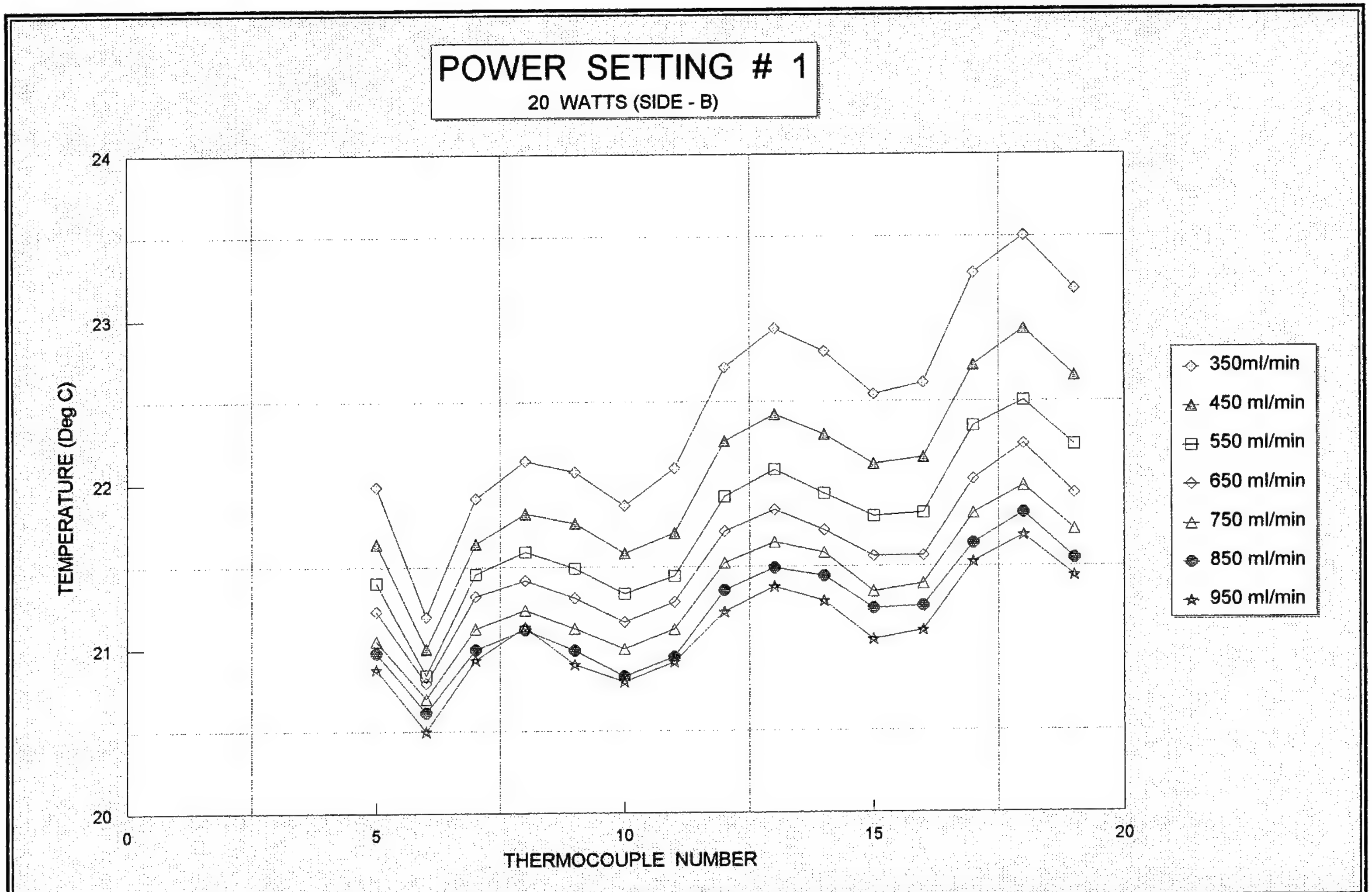


Figure 32. Temperature Distribution on the Module for Side - B, at Power Setting 1.

FTM SIDE - B

POWER SETTING # 2 (40 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	4.513	4.511	4.512	4.512	4.514	4.514	4.512
Heater -2	4.49	4.488	4.489	4.489	4.492	4.492	4.489
Heater -3	4.457	4.454	4.455	4.456	4.459	4.459	4.456
Heater -4	4.247	4.298	4.29	4.284	4.236	4.259	4.29
Heater -5	4.444	4.442	4.443	4.443	4.446	4.446	4.444
Heater -6	4.481	4.478	4.48	4.481	4.484	4.483	4.48
Heater -7	4.449	4.446	4.448	4.448	4.451	4.451	4.448
Heater -8	4.45	4.448	4.449	4.45	4.452	4.452	4.45
Heater -9	4.511	4.509	4.51	4.511	4.513	4.513	4.511
TOT. POW.	**40.042**	**40.074**	**40.076**	**40.074**	**40.047**	**40.069**	**40.08**
Av. Sur. T.	23.83	23.13	22.67	22.34	22.18	21.97	21.87
T in	20.85	20.8	20.69	20.65	20.65	20.58	20.58
T out	24.91	23.89	23.26	22.8	22.57	22.27	22.1
DENSITY	0.792	0.7924	0.7927	0.7929	0.793	0.7932	0.7932
SP.HEAT	2.0656	2.0632	2.0615	2.0604	2.0599	2.0591	2.0587
Q fluid	38.74	37.89	38.5	38.05	39.2	39.1	39.3
Q ins	0	-0.04	-0.06	-0.08	-0.08	-0.1	-0.1
Q total	**38.74**	**37.85**	**38.44**	**37.97**	**39.12**	**39**	**39.2**
DELTA Q	-1.302	-2.224	-1.636	-2.104	-0.927	-1.069	-0.88
DT ins	-0.1	-0.96	-1.39	-1.74	-1.84	-2.11	-2.22
DT fluid	4.08	3.11	2.62	2.14	1.91	1.72	1.44

THERMOCOUPLE READINGS

T/C -0	23.45	23.68	23.98	23.61	24.32	24.33	24.88
T/C -1	29.03	28.51	28.14	27.8	27.66	27.53	27.39
T/C -2	23.93	24.09	24.06	24.08	24.02	24.08	24.09
T/C -3	20.89	20.87	20.77	20.68	20.69	20.63	20.7
T/C -4	24.97	23.98	23.39	22.82	22.6	22.35	22.14
T/C -5	22.94	22.38	21.99	21.71	21.59	21.47	21.36
T/C -6	21.3	21.18	21	20.93	20.9	20.78	20.79
T/C -7	22.84	22.37	22.09	21.91	21.82	21.64	21.62
T/C -8	23.27	22.73	22.4	22.21	22.07	21.87	21.87
T/C -9	23.03	22.48	22.11	21.89	21.73	21.62	21.51
T/C -10	22.72	22.16	21.81	21.55	21.46	21.27	21.23
T/C -11	23.1	22.51	22.09	21.8	21.68	21.48	21.44
T/C -12	24.4	23.57	23.08	22.68	22.53	22.25	22.14
T/C -13	24.82	23.95	23.35	22.93	22.74	22.44	22.35
T/C -14	24.3	23.51	23.02	22.68	22.44	22.29	22.06
T/C -15	24.04	23.23	22.73	22.34	22.15	21.93	21.78
T/C -16	24.13	23.32	22.8	22.43	22.23	21.99	21.92
T/C -17	25.45	24.41	23.81	23.35	23.1	22.83	22.65
T/C -18	25.9	24.84	24.19	23.67	23.42	23.11	22.95
T/C -19	25.28	24.25	23.6	23.07	22.85	22.54	22.42

Table 16. Power and Temperature Data for Side - B at Power Setting 2.

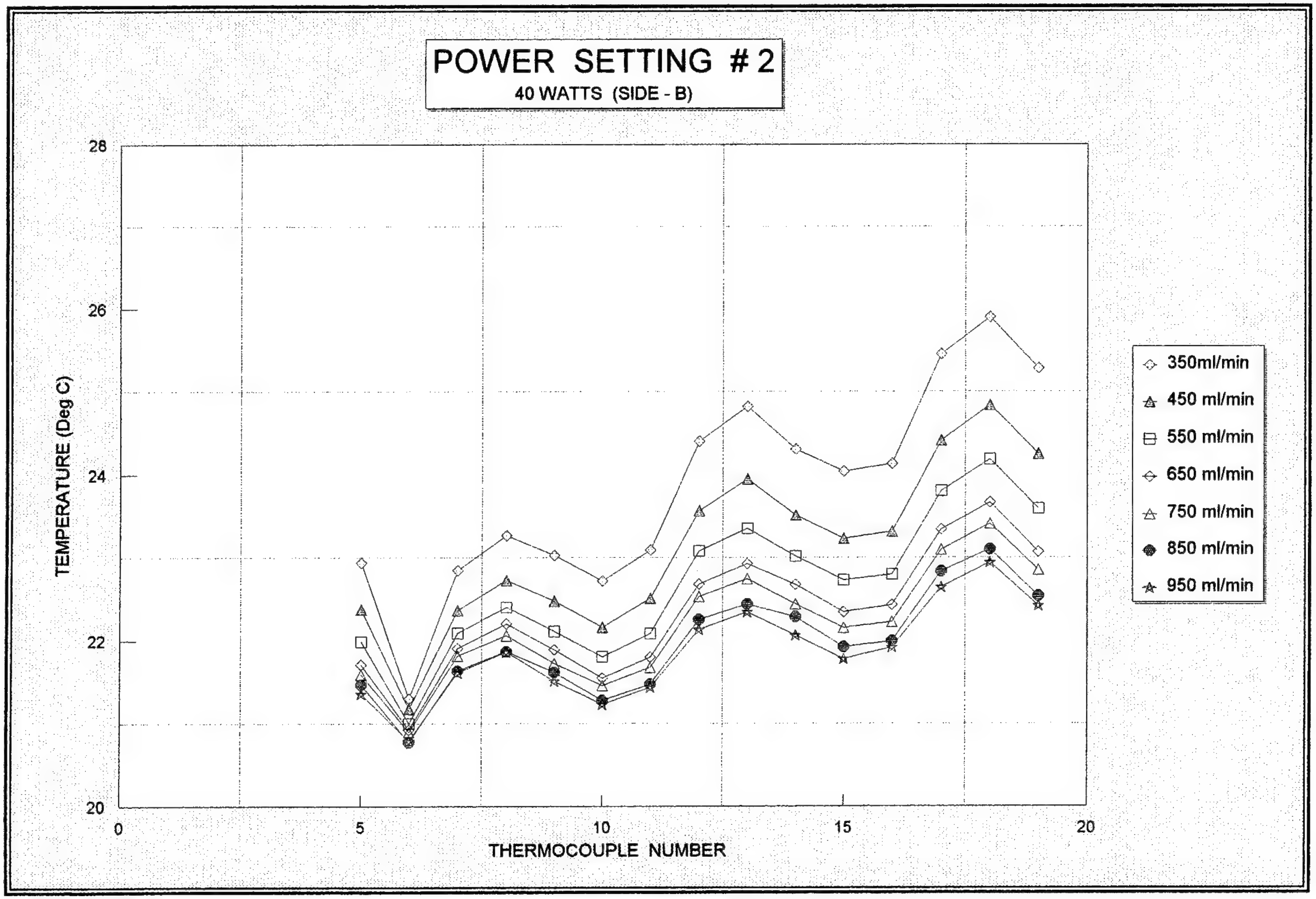


Figure 33. Temperature Distribution on the Module for Side - B, at Power Setting 2.

FTM SIDE - B

POWER SETTING # 3 (60 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	6.762	6.76	6.759	6.761	6.757	6.757	6.758
Heater -2	6.727	6.726	6.726	6.728	6.723	6.724	6.725
Heater -3	6.677	6.675	6.675	6.677	6.673	6.674	6.674
Heater -4	6.415	6.427	6.423	6.409	6.44	6.436	6.415
Heater -5	6.658	6.657	6.656	6.659	6.655	6.655	6.656
Heater -6	6.712	6.71	6.711	6.713	6.708	6.71	6.71
Heater -7	6.663	6.66	6.66	6.663	6.658	6.659	6.659
Heater -8	6.665	6.664	6.663	6.666	6.662	6.662	6.663
Heater -9	6.756	6.755	6.755	6.758	6.753	6.754	6.754
TOT. POW.	**60.035**	**60.034**	**60.028**	**60.034**	**60.029**	**60.031**	**60.014**
Av. Sur. T.	25.57	24.41	23.79	23.4	23	22.76	22.55
T in	21.27	20.99	20.84	20.83	20.71	20.68	20.63
T out	27.15	25.57	24.67	24.09	23.55	23.21	22.91
DENSITY	0.7908	0.7916	0.7921	0.7923	0.7926	0.7927	0.7929
SP.HEAT	2.0715	2.0673	2.065	2.0637	2.0622	2.0614	2.0606
Q fluid	56.19	56.21	57.43	57.75	58.02	58.57	58.98
Q ins	-0.02	-0.08	-0.1	-0.11	-0.12	-0.13	-0.14
Q total	**56.17**	**56.13**	**57.33**	**57.64**	**57.9**	**58.44**	**58.84**
DELTA Q	-3.865	-3.904	-2.698	-2.394	-2.129	-1.591	-1.174
DT ins	-0.4	-1.79	-2.2	-2.42	-2.72	-2.87	-3
DT fluid	5.87	4.63	3.83	3.26	2.9	2.56	2.24

THERMOCOUPLE READINGS

T/C -0	19.37	19.6	19.54	19.71	19.69	19.71	19.69
T/C -1	33.81	32.97	32.25	31.87	31.45	31.26	31.08
T/C -2	25.97	26.2	25.99	25.82	25.72	25.63	25.55
T/C -3	21.35	21.05	20.93	20.9	20.79	20.75	20.74
T/C -4	27.22	25.68	24.76	24.16	23.69	23.31	22.98
T/C -5	24.21	23.2	22.79	22.42	22.1	21.98	21.74
T/C -6	21.99	21.51	21.27	21.22	21.06	21.02	20.95
T/C -7	24.17	23.41	22.96	22.74	22.43	22.31	22.16
T/C -8	24.72	23.87	23.4	23.13	22.76	22.61	22.44
T/C -9	24.44	23.46	22.95	22.65	22.38	22.17	21.98
T/C -10	23.93	22.99	22.52	22.26	21.91	21.73	21.62
T/C -11	24.55	23.4	22.91	22.53	22.23	22	21.85
T/C -12	26.35	25.05	24.36	23.9	23.51	23.19	22.95
T/C -13	26.91	25.54	24.79	24.31	23.78	23.51	23.3
T/C -14	26.28	25	24.3	23.92	23.45	23.14	22.9
T/C -15	25.86	24.57	23.87	23.38	23	22.71	22.44
T/C -16	25.99	24.72	24.02	23.56	23.08	22.82	22.61
T/C -17	27.91	26.36	25.52	24.92	24.45	24.09	23.79
T/C -18	28.57	26.94	26.02	25.42	24.85	24.49	24.18
T/C -19	27.69	26.12	25.16	24.6	24.02	23.63	23.33

Table 17. Power and Temperature Data for Side - B at Power Setting 3.

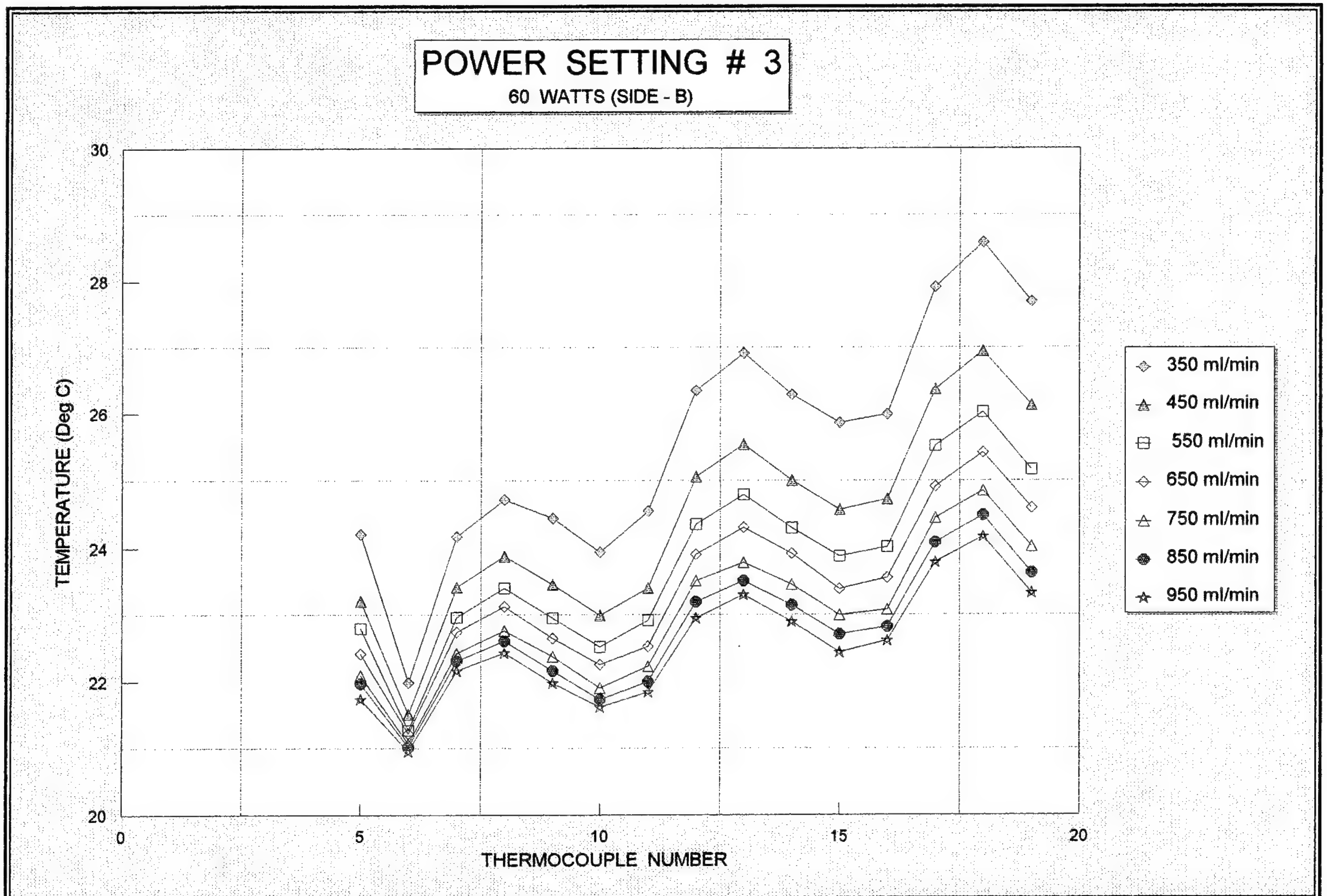


Figure 34. Temperature Distribution on the Module for Side - B, at Power Setting 3.

FTM SIDE - B

POWER SETTING # 4 (80 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	8.999	9.003	9.002	9.003	9.004	9.002	9.003
Heater -2	8.954	8.958	8.958	8.958	8.959	8.958	8.959
Heater -3	8.886	8.891	8.89	8.891	8.891	8.892	8.892
Heater -4	8.653	8.657	8.651	8.644	8.638	8.63	8.628
Heater -5	8.861	8.866	8.865	8.866	8.868	8.866	8.867
Heater -6	8.931	8.936	8.937	8.937	8.938	8.939	8.938
Heater -7	8.864	8.868	8.867	8.868	8.868	8.868	8.868
Heater -8	8.868	8.872	8.871	8.873	8.874	8.872	8.873
Heater -9	8.989	8.994	8.994	8.995	8.996	8.996	8.996
TOT. POW.	**80.005**	**80.045**	**80.035**	**80.035**	**80.036**	**80.023**	**80.024**
Av. Sur. T.	26.81	25.4	24.68	24.11	23.74	23.37	23.09
T in	20.99	20.89	20.86	20.79	20.73	20.71	20.67
T out	29	26.97	25.95	25.11	24.53	24.05	23.67
DENSITY	0.7902	0.7911	0.7915	0.7919	0.7922	0.7924	0.7925
SP.HEAT	2.075	2.0702	2.0679	2.0659	2.0644	2.0633	2.0624
Q fluid	76.61	74.68	76.37	76.56	77.68	77.36	77.64
Q ins	0.06	-0.03	-0.07	-0.1	-0.11	-0.12	-0.13
Q total	**76.67**	**74.65**	**76.3**	**76.46**	**77.57**	**77.24**	**77.51**
DELTA Q	-3.335	-5.395	-3.735	-3.575	-2.466	-2.783	-2.514
DT ins	1.24	-0.72	-1.49	-2.09	-2.4	-2.7	-2.94
DT fluid	8.1	6.05	5.11	4.27	3.76	3.38	3.02

THERMOCOUPLE READINGS

T/C -0	19.79	19.7	19.93	19.73	19.7	19.91	19.99
T/C -1	38.07	37.13	36.49	36.02	35.69	35.44	35.21
T/C -2	25.57	26.12	26.17	26.2	26.14	26.07	26.03
T/C -3	21.04	20.98	20.88	20.9	20.84	20.74	20.71
T/C -4	29.14	27.03	25.99	25.17	24.6	24.12	23.73
T/C -5	24.96	23.86	23.29	22.85	22.58	22.29	22.03
T/C -6	21.91	21.55	21.37	21.27	21.2	21.04	21.01
T/C -7	24.93	24.01	23.6	23.24	23.07	22.81	22.61
T/C -8	25.68	24.67	24.14	23.68	23.5	23.22	22.92
T/C -9	25.21	24.13	23.58	23.16	22.89	22.59	22.37
T/C -10	24.65	23.51	22.96	22.52	22.26	22.02	21.83
T/C -11	25.39	24.15	23.51	22.99	22.7	22.4	22.18
T/C -12	27.87	26.29	25.45	24.82	24.37	23.96	23.68
T/C -13	28.65	26.86	26.06	25.31	24.87	24.46	24.05
T/C -14	27.67	26.11	25.33	24.76	24.22	23.82	23.54
T/C -15	27.16	25.6	24.73	24.1	23.64	23.3	22.96
T/C -16	27.4	25.82	24.95	24.37	23.87	23.43	23.14
T/C -17	30.05	28.02	27	26.22	25.6	25.06	24.66
T/C -18	30.94	28.79	27.69	26.75	26.2	25.62	25.22
T/C -19	29.73	27.64	26.5	25.65	25.07	24.5	24.1

Table 18. Power and Temperature Data for Side - B, at Power Setting 4.

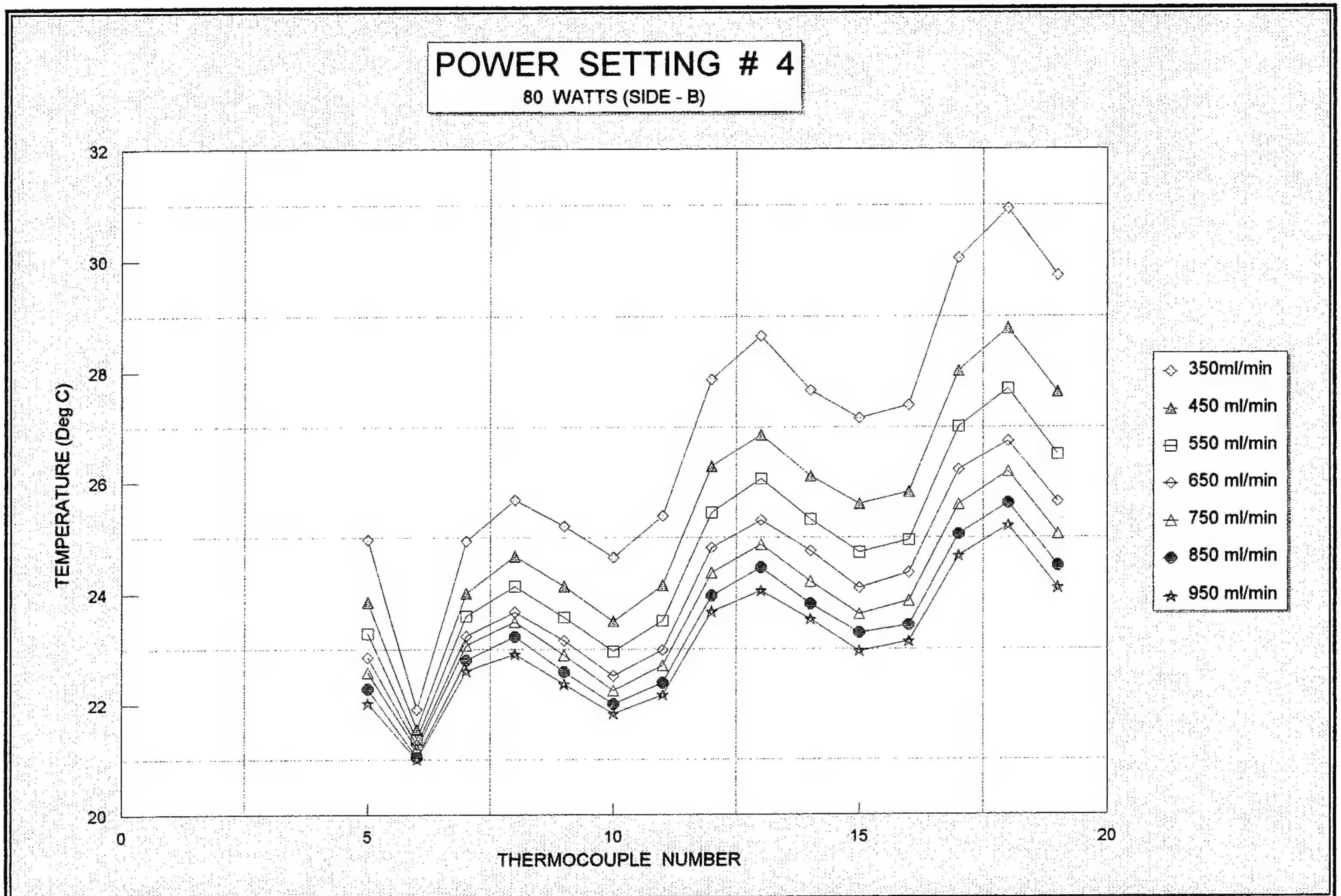


Figure 35. Temperature Distribution on the Module for Side - B, at Power Setting 4.

FTM SIDE - B

POWER SETTING # 5 (100 WATTS)

Flow Rate	350	450	550	650	750	850	950
	POWER	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**	**POWER**
Heater -1	11.235	11.239	11.244	11.24	11.238	11.239	11.24
Heater -2	11.179	11.183	11.188	11.185	11.183	11.184	11.185
Heater -3	11.094	11.098	11.104	11.101	11.098	11.1	11.101
Heater -4	10.915	10.919	10.925	10.922	10.92	10.921	10.922
Heater -5	11.063	11.068	11.073	11.07	11.069	11.07	11.071
Heater -6	11.149	11.154	11.161	11.158	11.156	11.158	11.159
Heater -7	11.062	11.066	11.071	11.067	11.065	11.067	11.067
Heater -8	11.067	11.072	11.077	11.074	11.073	11.073	11.075
Heater -9	11.218	11.224	11.23	11.227	11.225	11.227	11.228
TOT. POW.	**99.982**	**100.023**	**100.073**	**100.044**	**100.027**	**100.039**	**100.048**
Av. Sur. T.	27.88	26.2	25.28	24.72	24.19	23.76	23.43
T in	20.71	20.53	20.48	20.48	20.42	20.42	20.36
T out	30.59	28.22	26.84	26.05	25.18	24.63	24.15
DENSITY	0.7896	0.7907	0.7913	0.7916	0.792	0.7923	0.7925
SP.HEAT	2.0779	2.0722	2.069	2.0673	2.0652	2.064	2.0628
Q fluid	94.56	94.5	95.45	98.75	97.32	97.53	98.1
Q ins	0.03	-0.06	-0.09	-0.1	-0.11	-0.12	-0.13
Q total	**94.59**	**94.44**	**95.36**	**98.65**	**97.21**	**97.41**	**97.97**
DELTA Q	-5.392	-5.583	-4.713	-1.394	-2.817	-2.629	-2.078
DT ins	0.73	-1.2	-1.93	-2.09	-2.47	-2.72	-2.88
DT fluid	9.91	7.68	6.34	5.6	4.83	4.18	3.78

THERMOCOUPLE READINGS

T/C -0	19.72	19.57	19.61	19.82	19.78	19.71	19.75
T/C -1	43.11	41.85	41.06	40.5	39.91	39.55	39.28
T/C -2	27.15	27.4	27.21	26.81	26.66	26.48	26.31
T/C -3	20.77	20.63	20.58	20.54	20.48	20.53	20.46
T/C -4	30.68	28.31	26.92	26.14	25.31	24.71	24.24
T/C -5	25.64	24.21	23.51	23.08	22.66	22.35	22.1
T/C -6	21.93	21.45	21.18	21.05	21.01	20.92	20.8
T/C -7	25.52	24.53	23.96	23.58	23.34	23.06	22.82
T/C -8	26.56	25.26	24.67	24.24	23.88	23.54	23.3
T/C -9	25.96	24.63	23.92	23.48	23.02	22.72	22.48
T/C -10	25.19	23.8	23.12	22.71	22.36	22.13	21.83
T/C -11	26.08	24.56	23.77	23.28	22.92	22.52	22.23
T/C -12	29.14	27.25	26.17	25.59	25.02	24.44	24.08
T/C -13	30.18	28.11	26.99	26.35	25.61	25.13	24.69
T/C -14	28.96	27.13	26.05	25.35	24.8	24.3	23.97
T/C -15	28.26	26.44	25.33	24.76	24.14	23.62	23.25
T/C -16	28.57	26.69	25.63	25.03	24.4	23.92	23.54
T/C -17	31.86	29.49	28.22	27.35	26.49	25.91	25.46
T/C -18	33.02	30.46	29.04	28.14	27.31	26.6	26.08
T/C -19	31.4	28.97	27.6	26.76	25.89	25.24	24.76

Table 19. Power and Temperature Data for Side - B, at Power Setting 5.

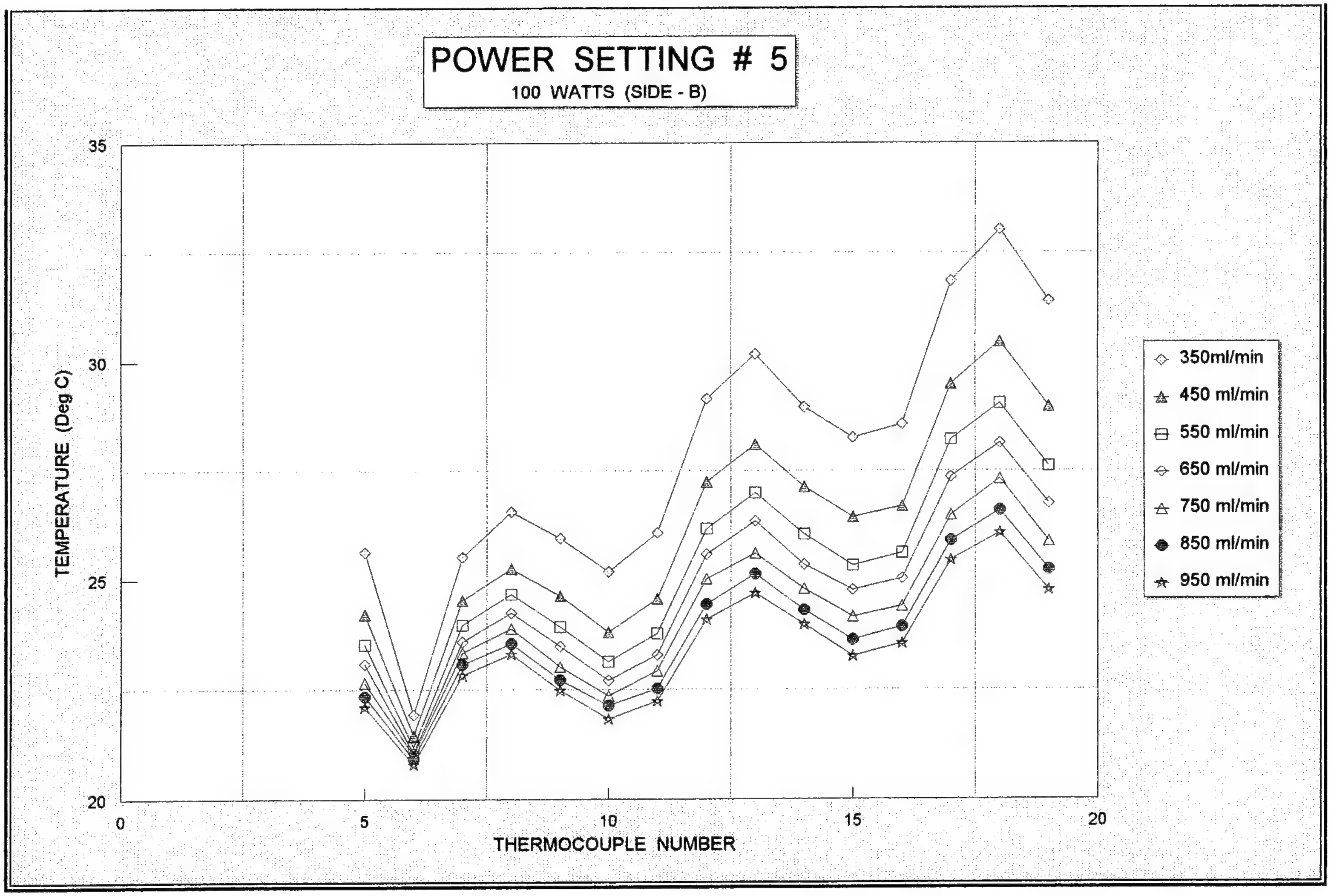


Figure 36. Temperature Distribution on the Module for Side - B, at Power Setting 5.

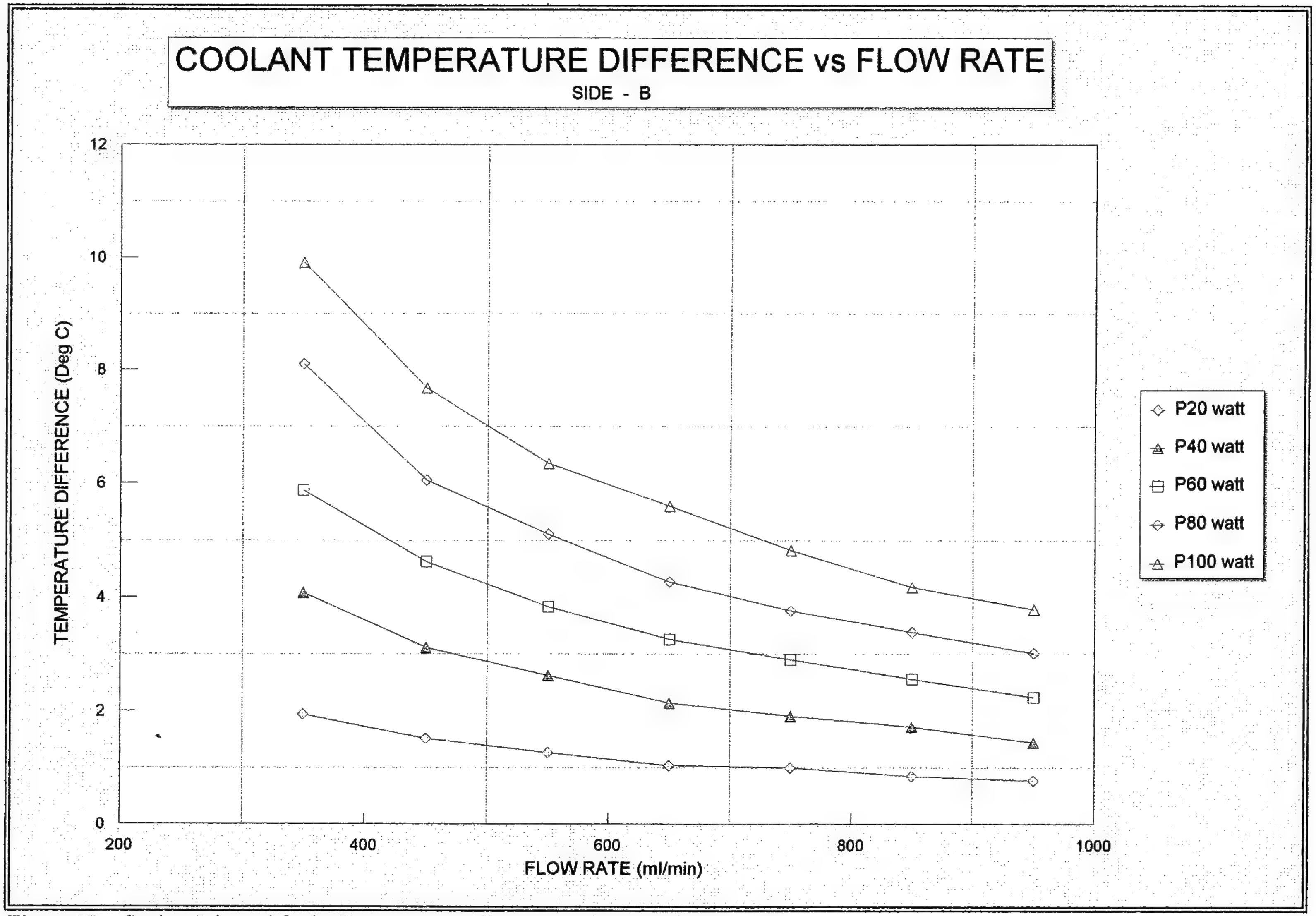


Figure 37. Coolant Inlet and Outlet Temperature Difference vs Flow Rate for Side - B.

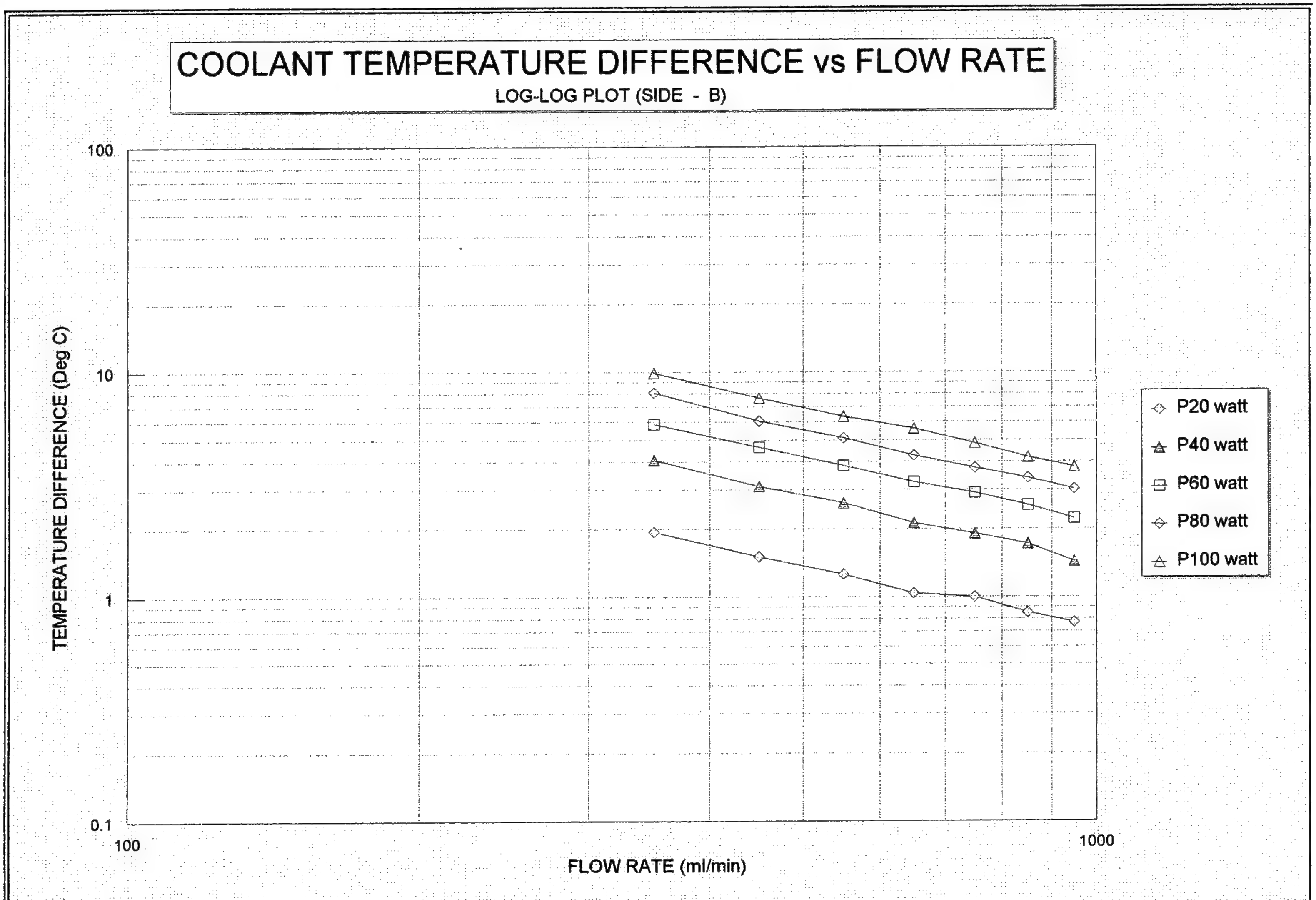


Figure 38. Logarithmic Plot of Coolant Inlet and Outlet Temperature Difference vs Flow Rate for Side - B.

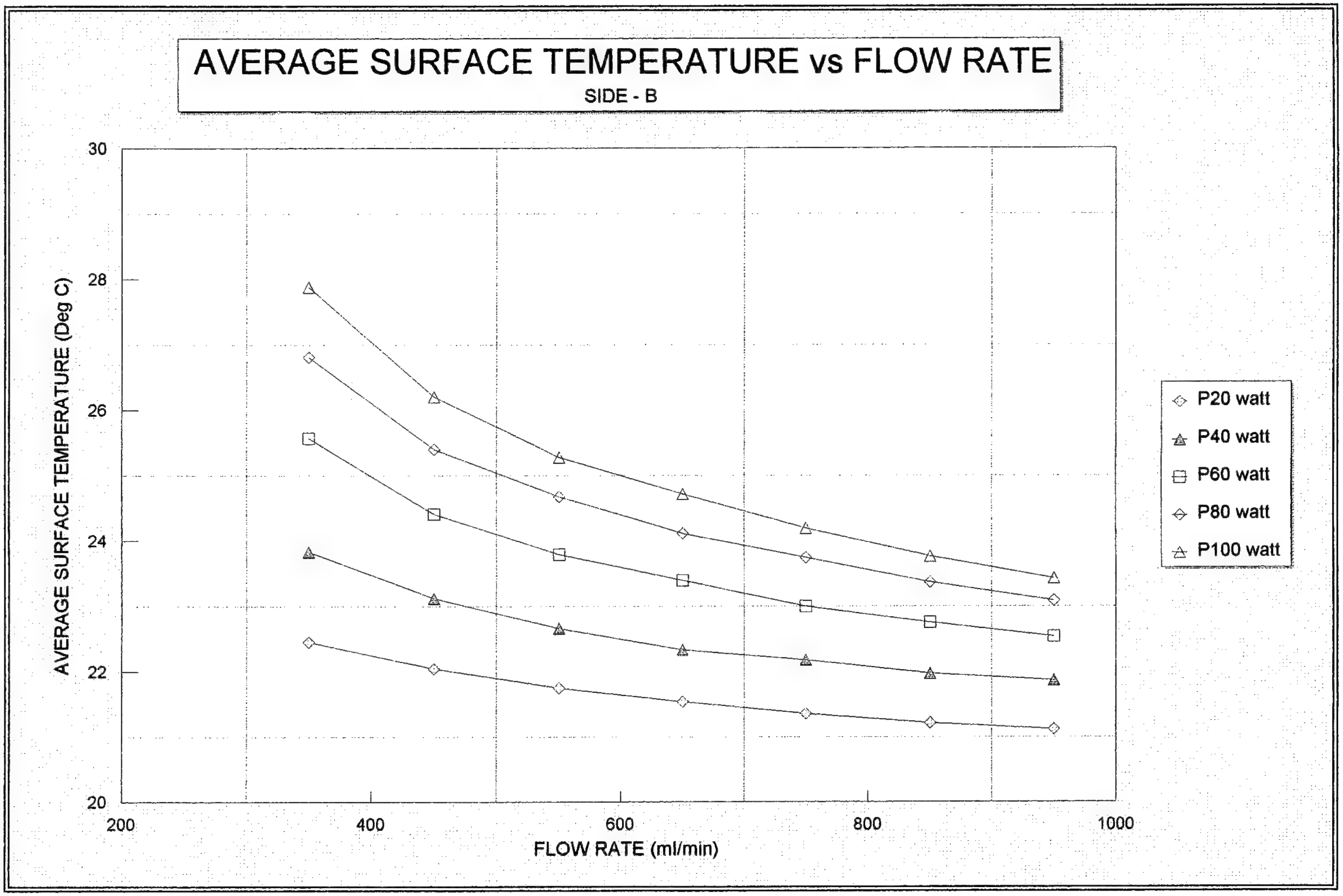


Figure 39. Average Surface Temperature vs Flow Rate for Side - B.

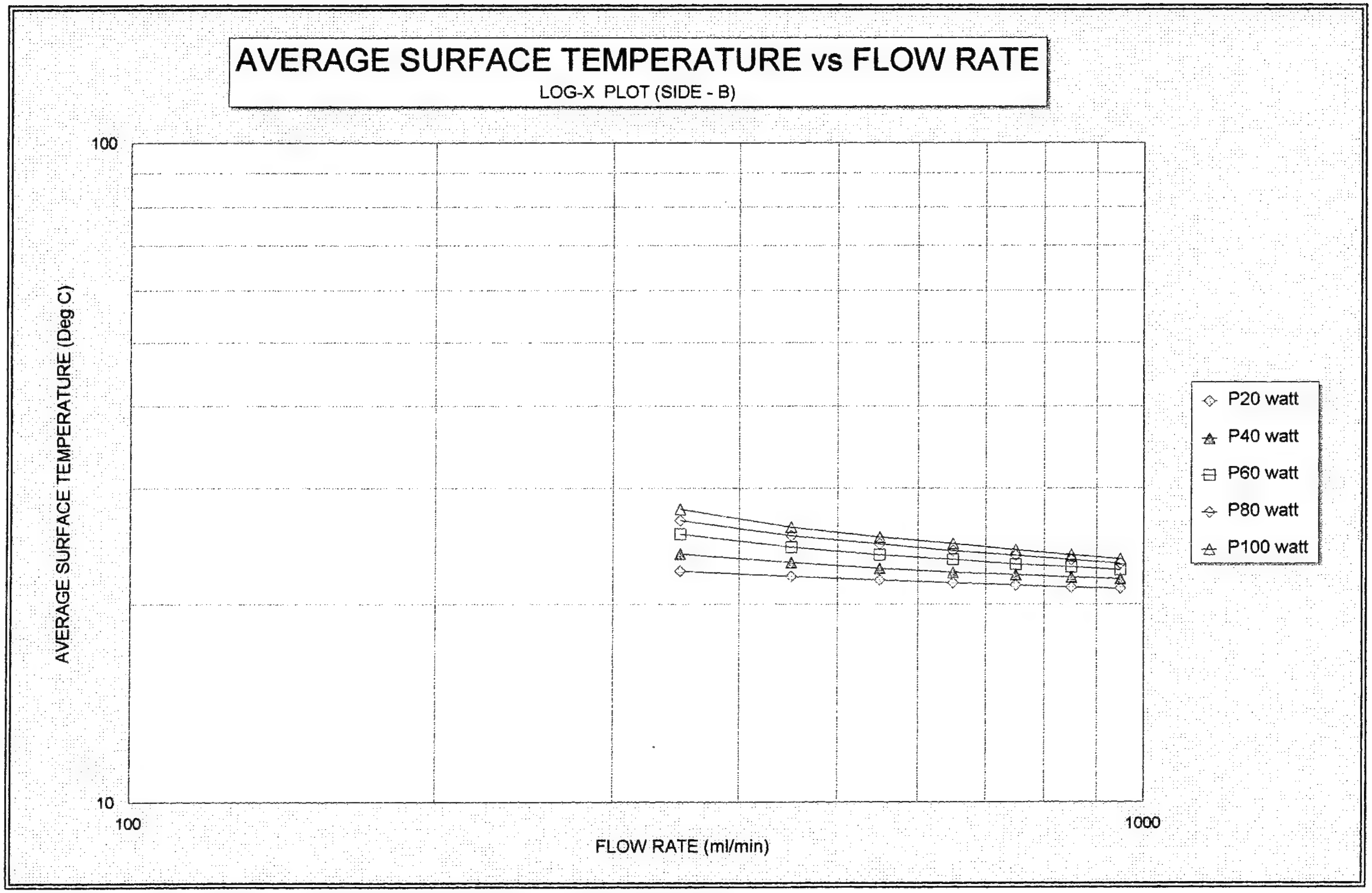


Figure 40. Log-Log Plot of Average Surface Temperature vs Flow Rate for Side - B.

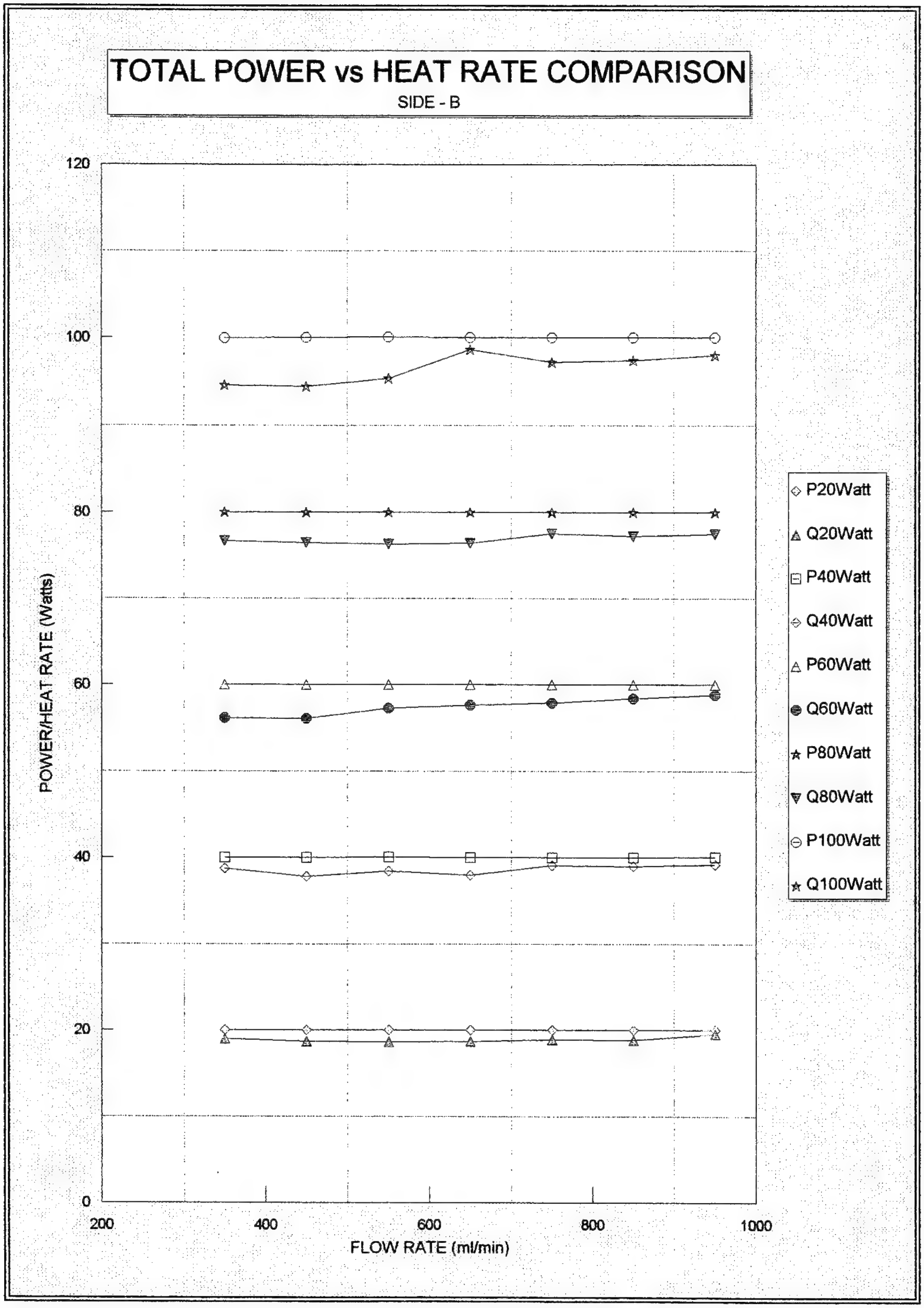


Figure 41. Total Power vs. Heat Rate Comparison for Side - B.

B. FORMULATION OF THE CORRELATIONS

The correlation calculations are based on some assumptions made for the free flow area, A_f and the log mean temperature difference, ΔT_{LM}. The assumption for the free flow area is made due to the uncertainty of the inner dimensions of the FTM. This assumption is made for the width of the 3 parallel passages in order to calculate the number of channels in a passage shown in Figure 7 and detailed in Figure 42.

Heating of the FTM would not fit either the "constant surface heat flux" case, or the "constant wall temperature" case. Therefore the log-mean temperature difference was defined for the experiments as follows:

$$\Delta T_{LM} = \frac{\left(T_{surf,out} - \bar{T}_{out}\right) - \left(T_{surf,in} - \bar{T}_{in}\right)}{\ln\left[\left(T_{surf,out} - \bar{T}_{out}\right) \div \left(T_{surf,in} - \bar{T}_{in}\right)\right]} \tag{17}$$

$$= \frac{\left(T(19) - \bar{T}\right) - \left(T(5) - \bar{T}_{in}\right)}{\ln\left[\left(T(19) - \bar{T}\right) \div \left(T(5) - \bar{T}_{in}\right)\right]}$$

The rest of the necessary data is available in order to be able to calculate the *Reynolds* and the *Stanton* numbers. The equations utilized for the calculations of these quantities are as follows:

$$Re_{D_h} = \frac{U_m D_h}{\nu} \tag{18}$$

$$St = \frac{P_T}{\rho \dot{Q} c_p \Delta T_{LM}} \tag{19}$$

The hydraulic diameter is calculated by using the following equation and the dimensions defined for the fins, in Figure 6 and drawn in detail in Figure 42.

$$D_h = \frac{4A_c}{P} = \frac{4 \times 0.046 \times 0.06}{2 \times (0.046 + 0.06)} = 0.05208 in \equiv 1.323 \times 10^{-3} m \qquad (20)$$

The free flow area of the coolant through the three parallel passages of the FTM is evaluated with respect to the assumption made for the passage width (Figure 42) which is assumed to be 1.75 in. Since the fin density is known the free flow area is calculated as follows:

$$A_f = h \times b \times n \qquad (21)$$

$$= 0.06 \times 0.046 \times 34 = 0.09384 in^2 \equiv 6.0542 \times 10^{-5} m^2$$

where,

h: Height of a Channel.

b: Width of a Channel.

n: Number of Channels in a Passage in the Transverse Direction.

The average velocity of the coolant through the channels is calculated by using the following equation:

$$U_m = \frac{\dot{Q}}{A_f} \qquad (22)$$

Finally, the necessary information to evaluate the *Reynolds* and the *Stanton* numbers are available and the results are tabulated in Table 22 and plotted in Figures 43 through 58.

The relationship between *Reynolds* and *Stanton* numbers is formulated by utilizing the logarithmic plots. The results for each power setting are tabulated in Tables 20 and 21, for both sides of the FTM.

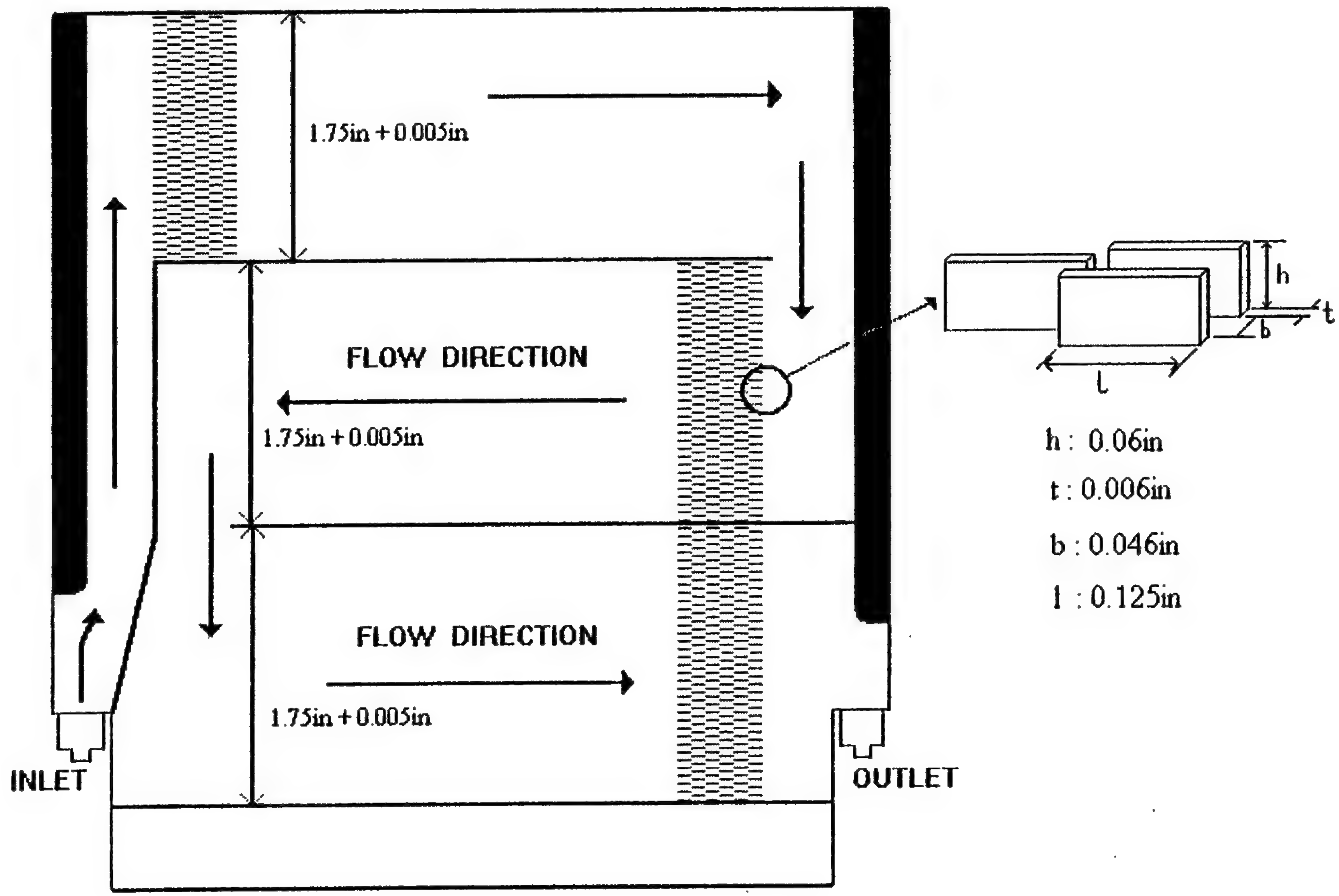


Figure 42. Estimated View and the Dimensions for the Inside of the FTM.

CORRELATION (*St* vs. *Re*)	TOTAL POWER (Watts)
$St = 0.100*Re^{-0.836}$	30
$St = 0.108*Re^{-0.793}$	50
$St = 0.111*Re^{-0.781}$	60
$St = 0.110*Re^{-0.785}$	70
$St = 0.120*Re^{-0.847}$	80
$St = 0.123*Re^{-0.836}$	90
$St = 0.130*Re^{-0.867}$	100

Table 20. Correlations for Side - A.

CORRELATION (*St* vs. *Re*)	TOTAL POWER (Watts)
$St = 0.084*Re^{-0.493}$	20
$St = 0.091*Re^{-0.324}$	40
$St = 0.098*Re^{-0.357}$	60
$St = 0.084*Re^{-0.163}$	80
$St = 0.101*Re^{-0.309}$	100

Table 21. Correlations for Side - B.

SIDE - A

30 watts							
Flow Rate	350	450	550	650	750	850	950
LogmeanT	0.938	0.901	0.867	0.837	0.796	0.804	0.769
St #	0.056	0.0454	0.0386	0.0339	0.0309	0.027	0.0252
Re #	2.03	2.58	3.12	3.66	4.19	4.73	5.29
U mean	0.096	0.124	0.151	0.179	0.206	0.234	0.262
Kinm.Visc.	0.000063	0.000064	0.000064	0.000065	0.000065	0.000065	0.000066

70 watts							
Flow Rate	350	450	550	650	750	850	950
LogmeanT	2.162	2.03	1.866	1.736	1.686	1.634	1.577
St #	0.0573	0.0468	0.0417	0.038	0.0339	0.0309	0.0286
Re #	2.36	2.87	3.4	3.95	4.48	5.04	5.58
U mean	0.096	0.124	0.151	0.179	0.206	0.234	0.262
Kinm.Visc.	0.000054	0.000057	0.000059	0.00006	0.000061	0.000061	0.000062

100 watts							
Flow Rate	350	450	550	650	750	850	950
LogmeanT	2.996	2.723	2.551	2.447	2.375	2.283	2.232
St #	0.0581	0.0498	0.0435	0.0384	0.0343	0.0315	0.0288
Re #	2.54	3.03	3.55	4.1	4.62	5.17	5.7
U mean	0.096	0.124	0.151	0.179	0.206	0.234	0.262
Kinm.Visc.	0.00005	0.000054	0.000056	0.000058	0.000059	0.00006	0.000061

SIDE - B

60 Watts							
Flow Rate	350	450	550	650	750	850	950
LogmeanT	1.416	1.194	1.057	0.95	0.848	0.779	0.71
St #	0.0739	0.0683	0.0631	0.0595	0.0577	0.0555	0.0545
Re #	2.29	2.81	3.32	3.88	4.39	4.94	5.48
U mean	0.096	0.124	0.151	0.179	0.206	0.234	0.262
Kinm.Visc.	0.000055	0.000058	0.00006	0.000061	0.000062	0.000063	0.000063

80 Watts							
Flow Rate	350	450	550	650	750	850	950
LogmeanT	1.913	1.545	1.265	1.135	1.064	0.9	0.808
St #	0.0729	0.0703	0.0703	0.0663	0.0613	0.064	0.0638
Re #	2.4	2.91	3.44	3.98	4.5	5.05	5.59
U mean	0.096	0.124	0.151	0.179	0.206	0.234	0.262
Kinm.Visc.	0.000053	0.000056	0.000058	0.00006	0.000061	0.000061	0.000062

100 Watts							
Flow Rate	350	450	550	650	750	850	950
LogmeanT	2.281	1.842	1.641	1.456	1.332	1.146	1.078
St #	0.0763	0.0736	0.0677	0.0646	0.0612	0.0628	0.0598
Re #	2.5	2.98	3.49	4.05	4.54	5.09	5.62
U mean	0.096	0.124	0.151	0.179	0.206	0.234	0.262
Kinm.Visc.	0.000051	0.000055	0.000057	0.000059	0.00006	0.000061	0.000062

Table 22. Reynolds and Stanton Number Data for Both Sides of the FTM.

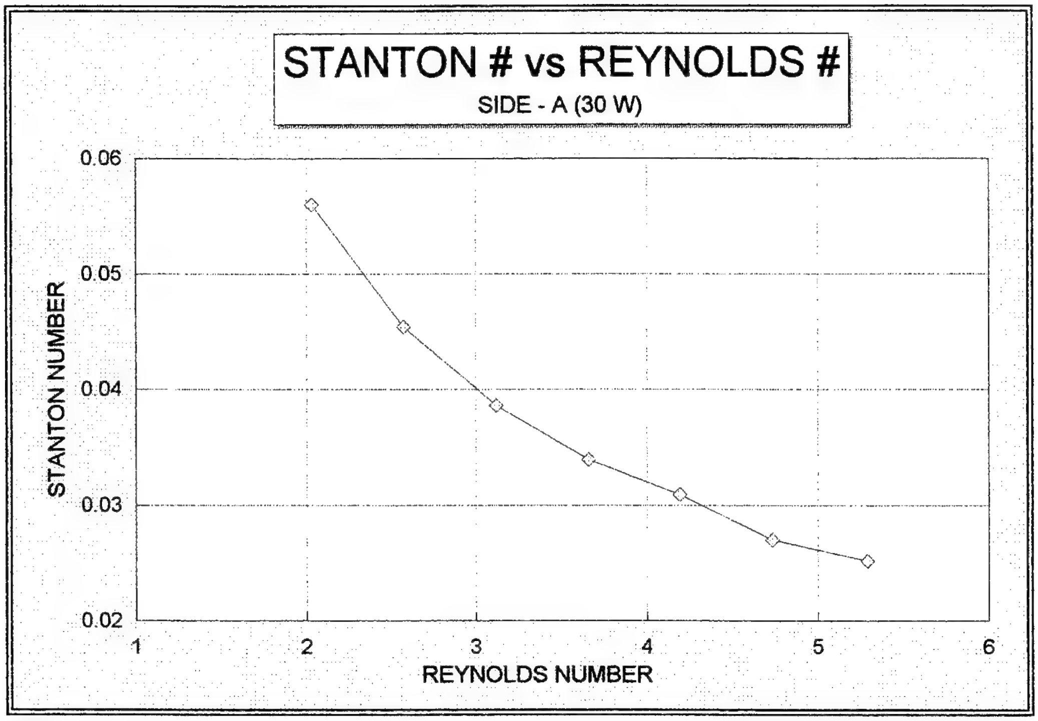


Figure 43. Linear Plot of Stanton vs. Reynolds Number for Side -A, at Power Setting 2.

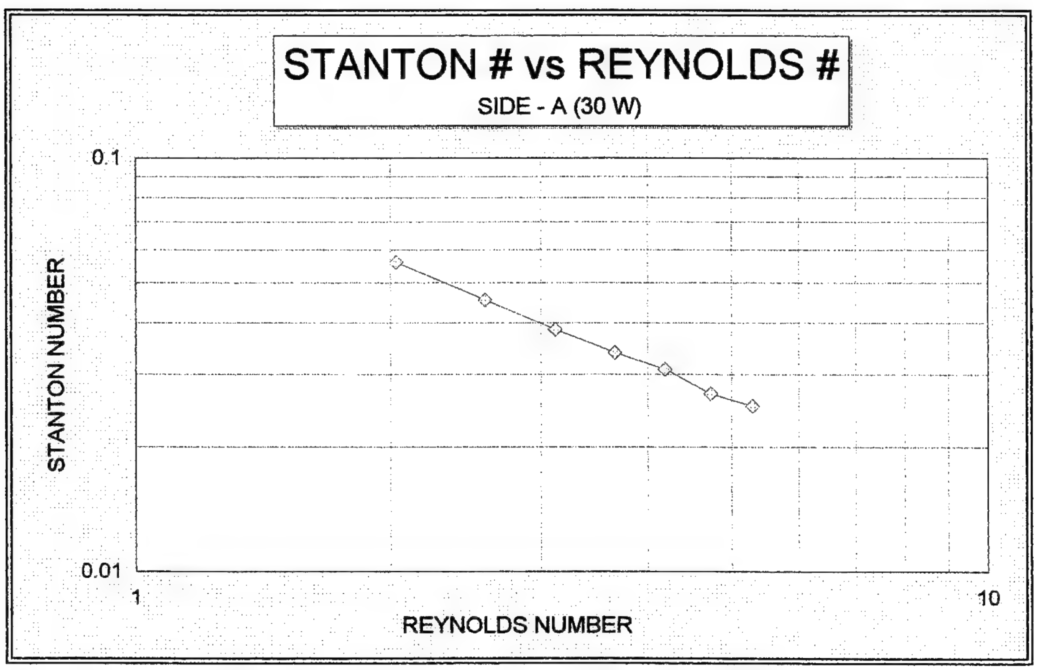


Figure 44. Logarithmic Plot of Stanton vs. Reynolds Number for Side -A, at Power Setting 2.

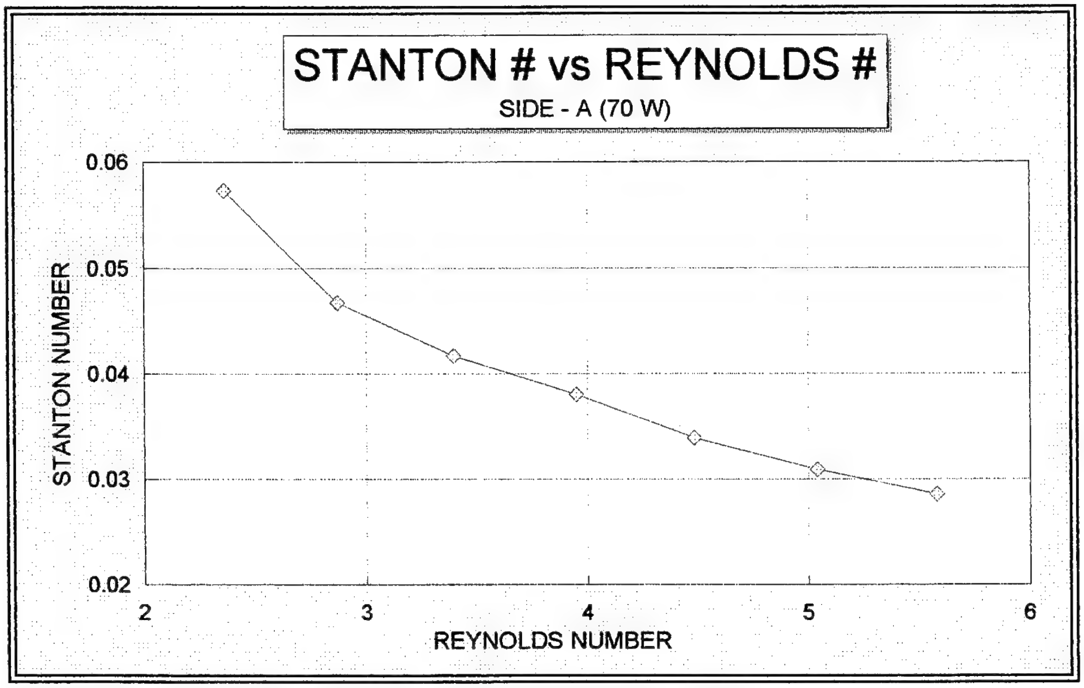


Figure 45. Linear Plot of Stanton vs. Reynolds Number for Side -A, at Power Setting 6.

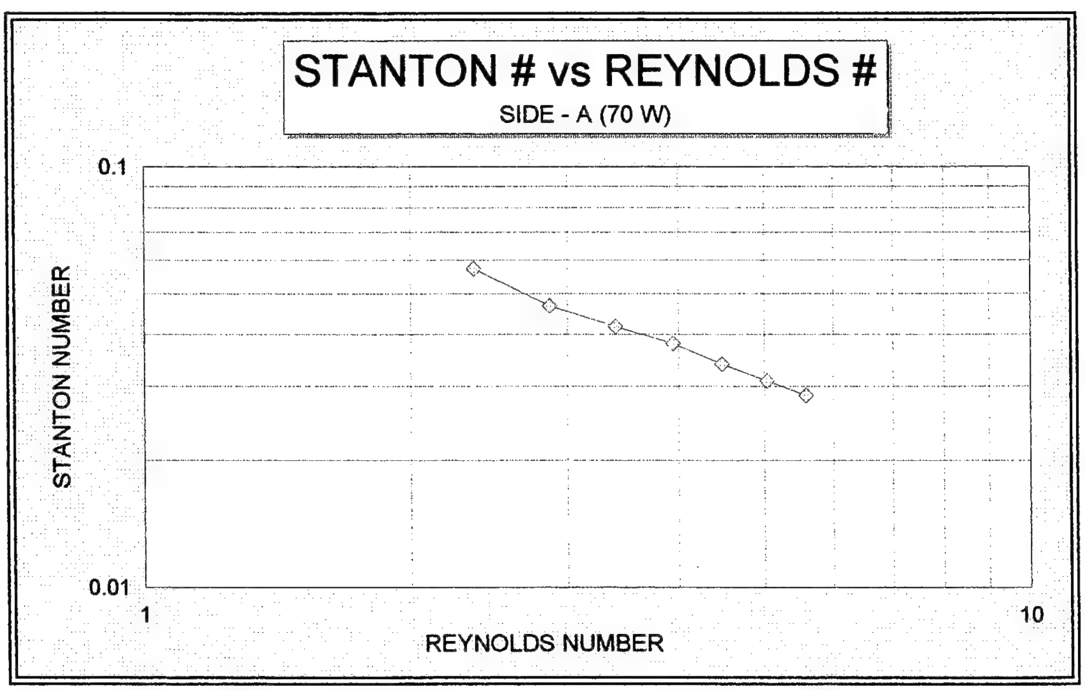


Figure 46. Logarithmic Plot of Stanton vs. Reynolds Number for Side -A, at Power Setting 6.

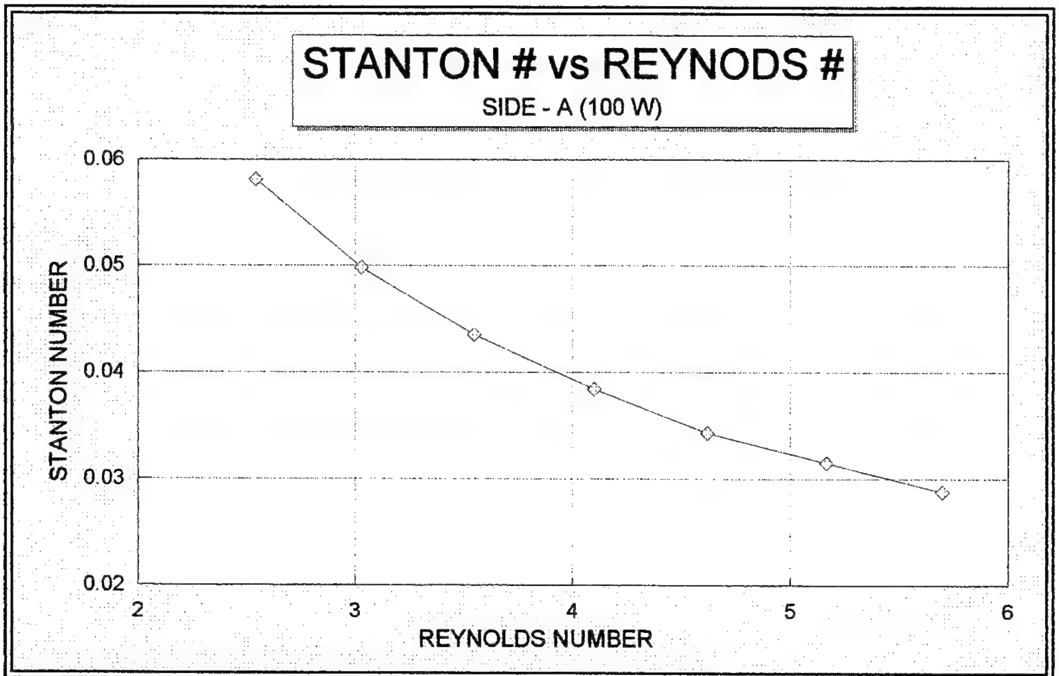


Figure 47. Linear Plot of Stanton vs. Reynolds Number for Side -A, at Power Setting 9.

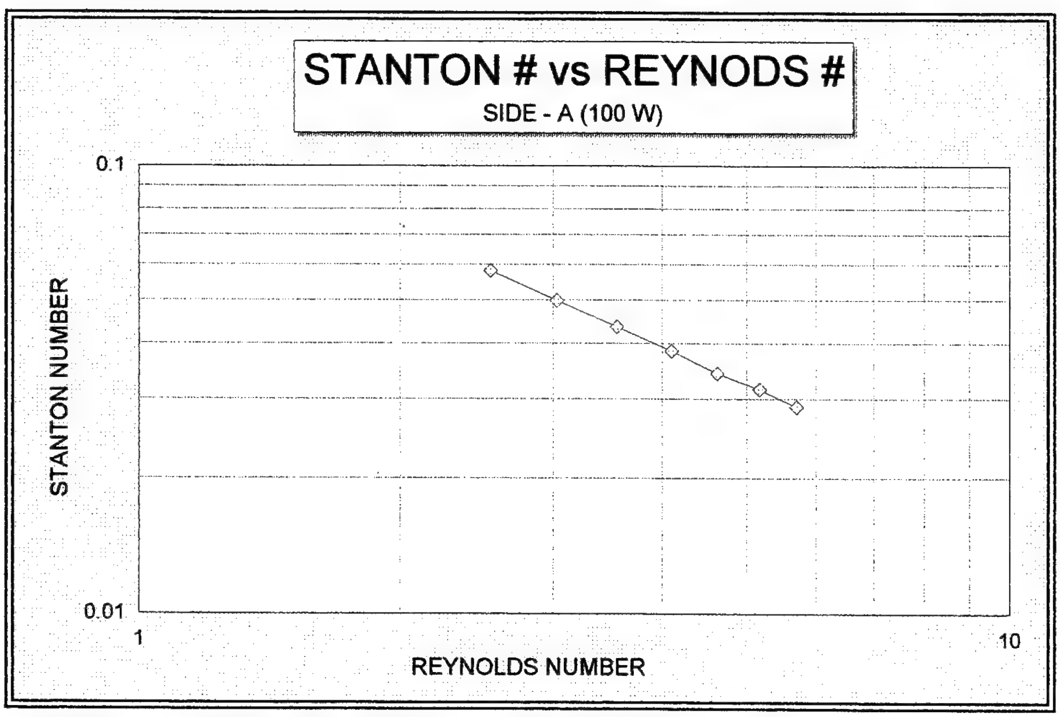


Figure 48. Logarithmic Plot of Stanton vs. Reynolds Number for Side -A, at Power Setting 9.

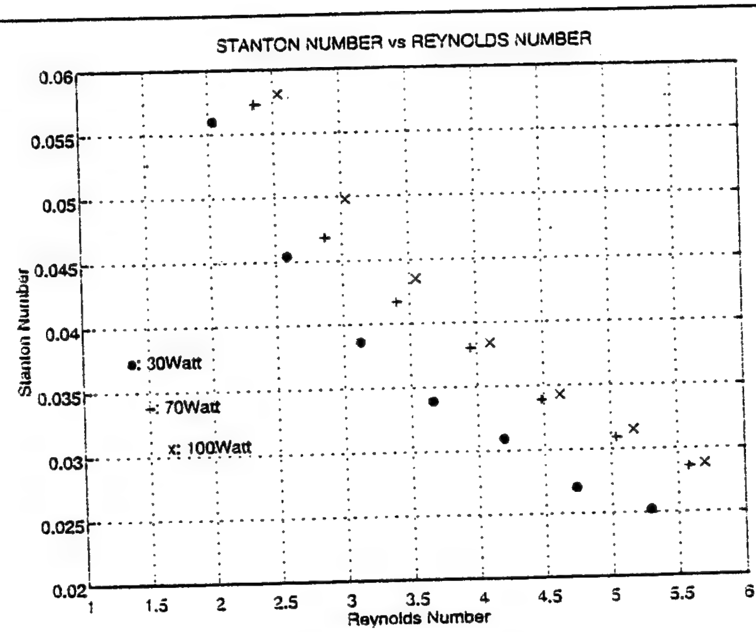


Figure 49. Linear Plot of Stanton vs. Reynolds Number for Side - A, at Power Settings 2,6 and 9.

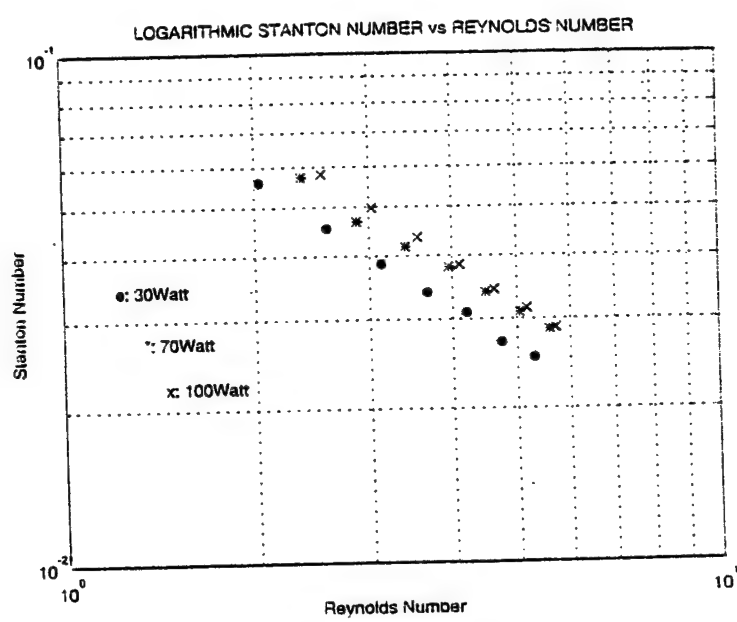


Figure 50. Logarithmic Plot of Stanton vs. Reynolds Number for Side - A, at Power Settings 2,6 and 9.

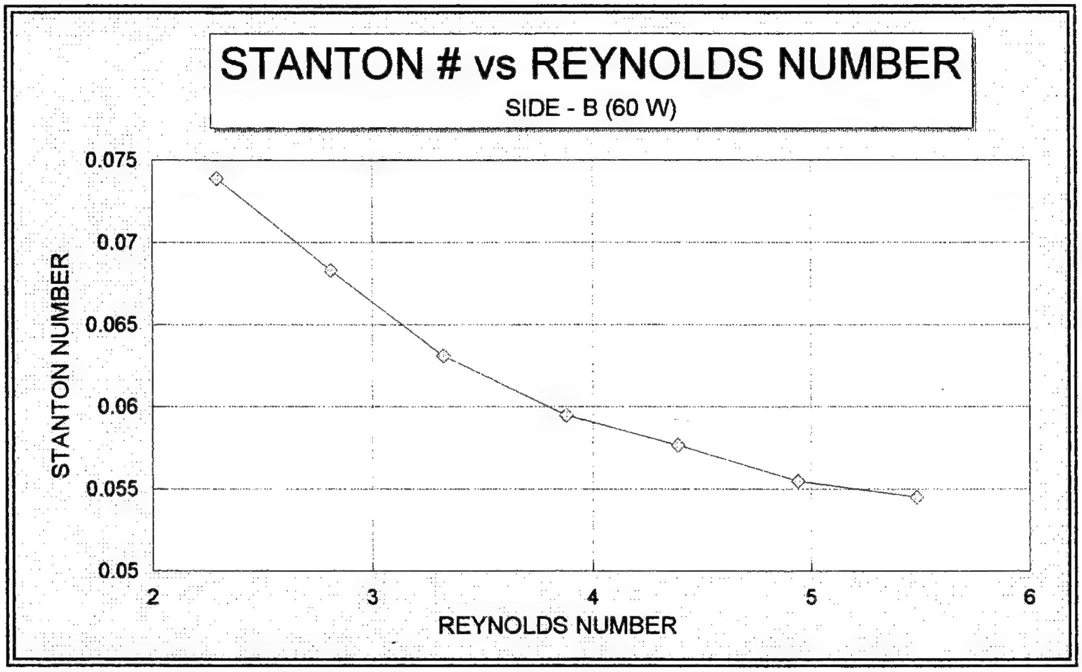


Figure 51. Linear Plot of Stanton vs. Reynolds Number for Side -B, at Power Setting 3.

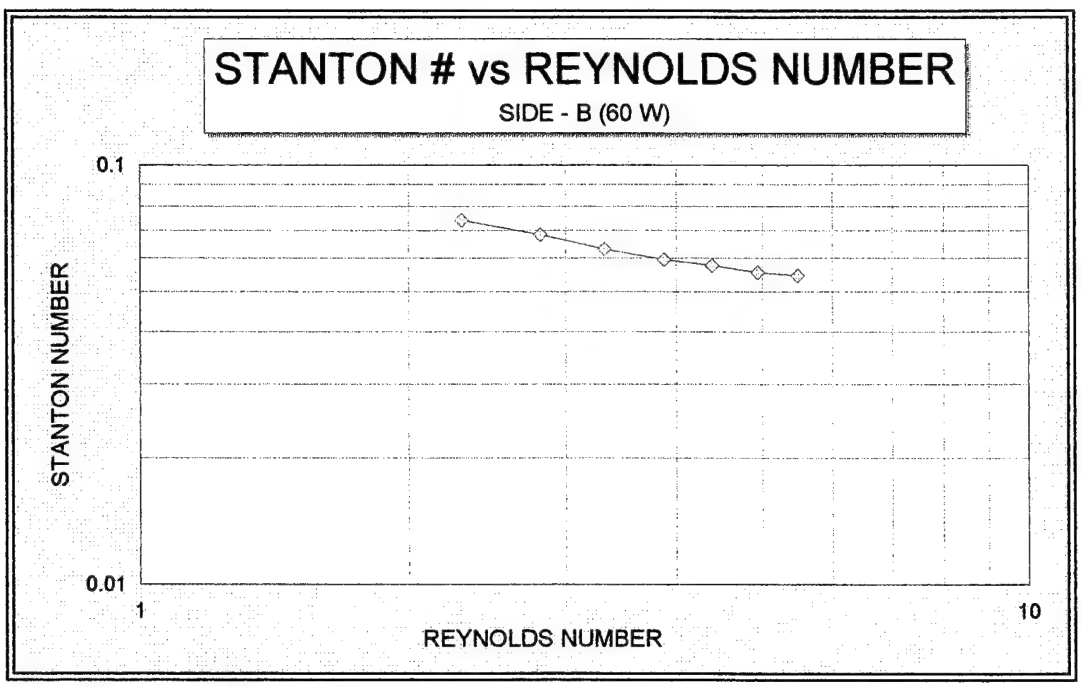


Figure 52. Logarithmic Plot of Stanton vs. Reynolds Number for Side -B, at Power Setting 3.

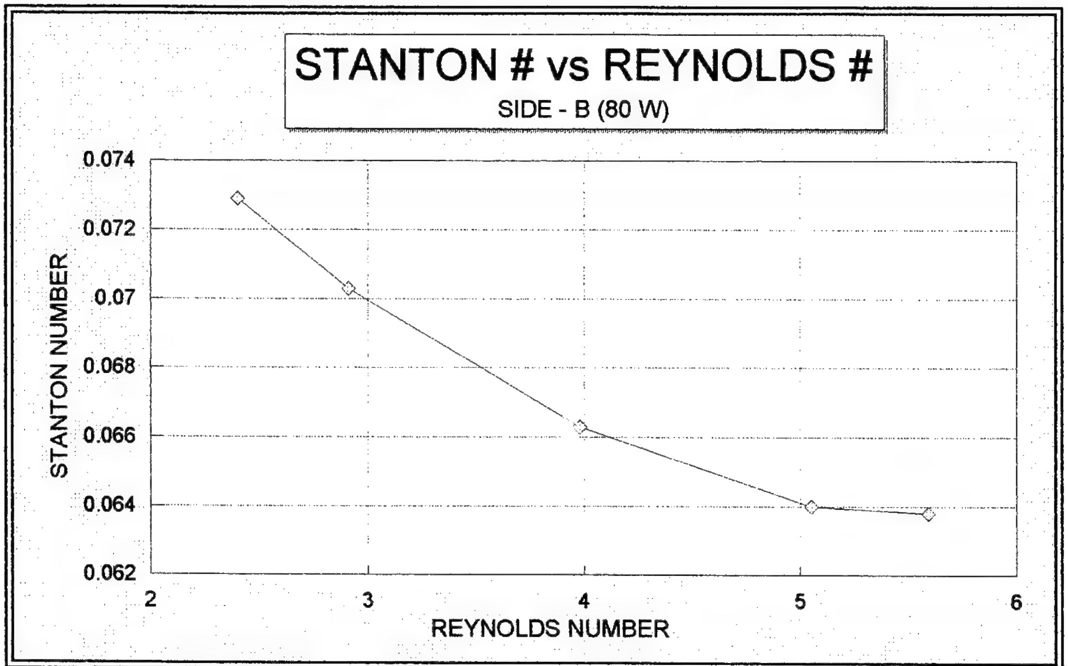


Figure 53. Linear Plot of Stanton vs. Reynolds Number for Side -B, at Power Setting 4.

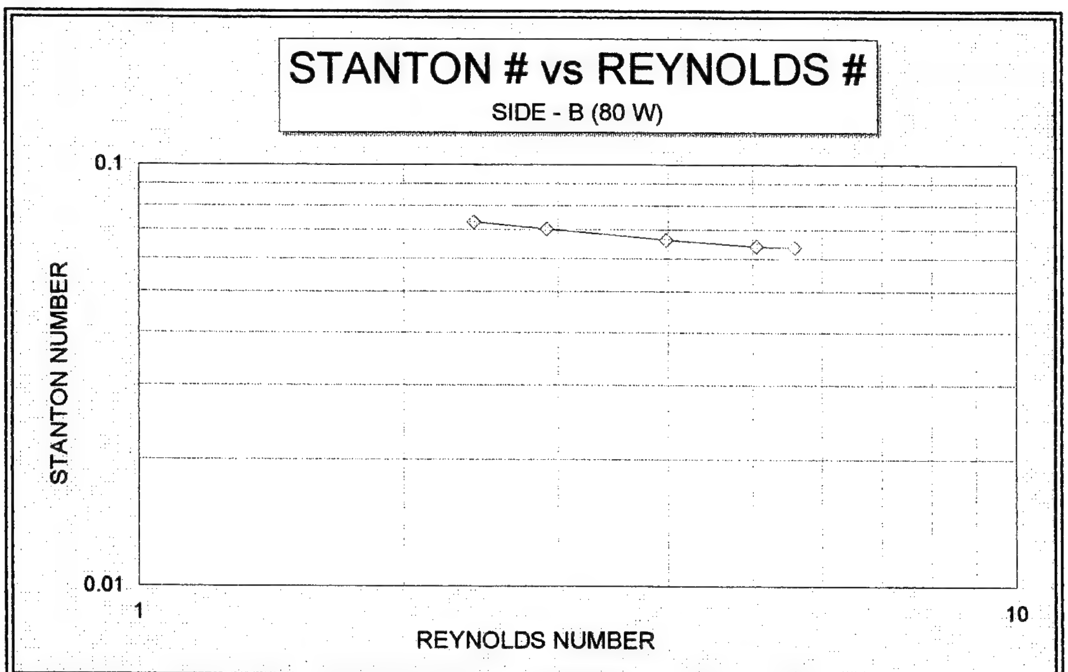


Figure 54. Logarithmic Plot of Stanton vs. Reynolds Number for Side -B, at Power Setting 4.

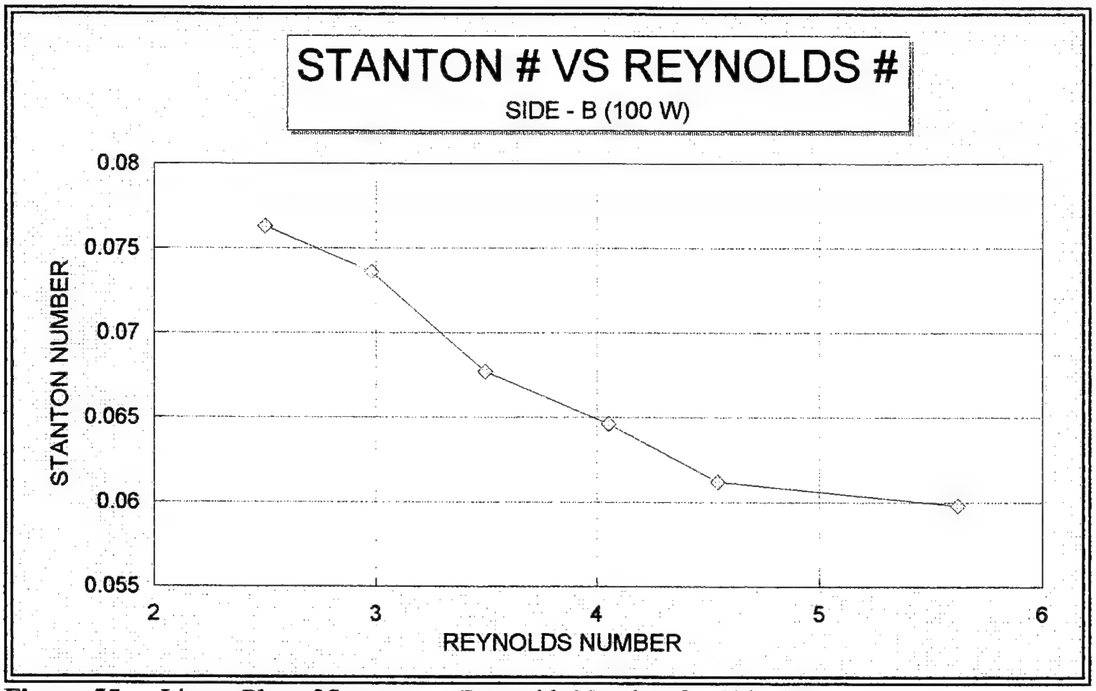


Figure 55. Linear Plot of Stanton vs. Reynolds Number for Side -B, at Power Setting 5.

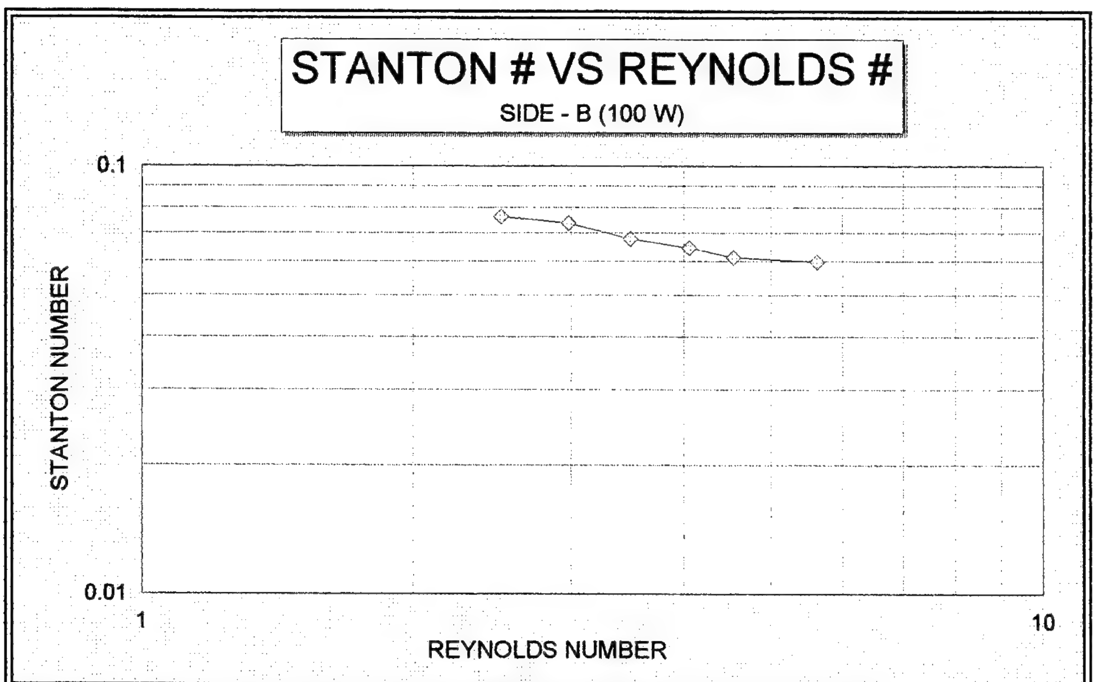


Figure 56. Logarithmic Plot of Stanton vs. Reynolds Number for Side -B, at Power Setting 5.

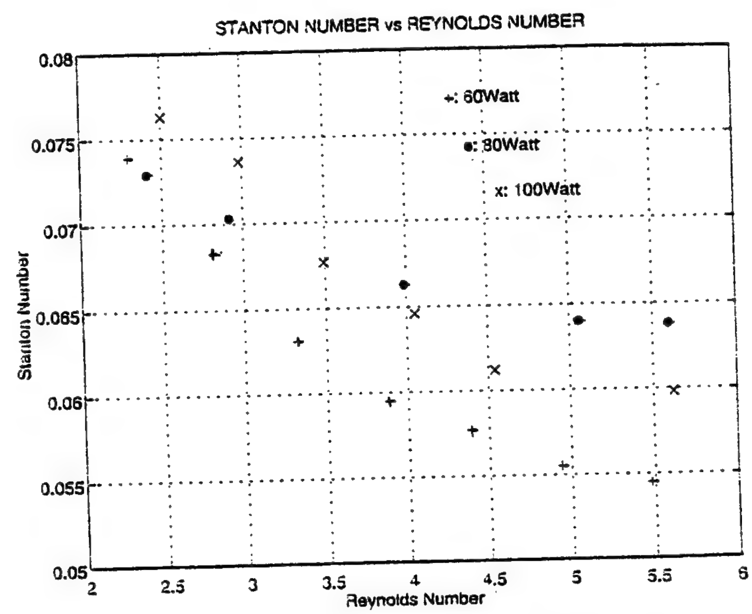


Figure 57. Linear Plot of Stanton vs. Reynolds Number for Side - B, at Power Settings 3,4 and 5.

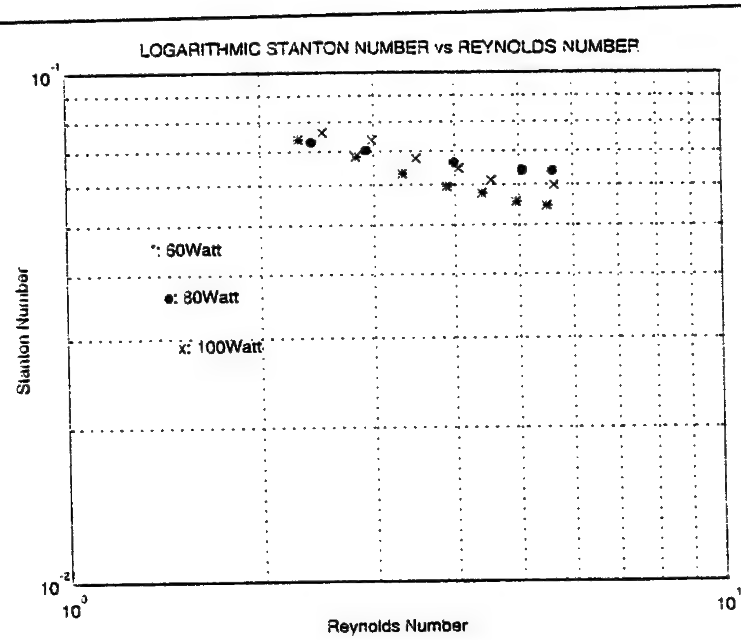


Figure 58. Logarithmic Plot of Stanton vs. Reynolds Number for Side - A, at Power Settings 3,4 and 5.

V. DISCUSSION AND CONCLUSIONS

Both sets of experiments conducted for Side-A and Side-B clearly showed the effectiveness and high cooling capacity of the FTM.

A. THE EXPERIMENTS CONDUCTED FOR SIDE-A

The thermocouple readings plotted in Figures -18 through 26 show the general trend of temperature rise along the first and third rows and temperature decrease in the second row of the flow path.

The decrease in the surface temperatures of the module, as shown in Figures -18 through 26, was observed more clearly during the changes of flow rates from 350ml/min to 450 ml/min and from 450 ml/min to 550 ml/min at all power settings. For the rest of the flow settings the decrease in surface temperatures were almost equal and actually the decrease varied logarithmically. The lowest temperature was measured at thermocouple 5, which was the first reading taken from the surface of the module. This low temperature occurred due to the which fins existed on the path from the inlet to that thermocouple location. On the other hand, the temperature on the surface of the module was measured at thermocouple location 18, which was before the last thermocouple affixed just after heater-F (Figure -12). The slope of temperature rise across the heaters is almost equal for the heaters A,B,C and E. This slope was steeper than the others, that is temperature rises across these heaters were more significant than heater D and F.

On the other hand, the temperature was observed to decrease across heater-D for all of the power and flow settings. This was explained by the counter-flow heat exchanger effect occurring between the inlet and the bend, between the second to the third rows. Significant negative slope was observed between thermocouple readings 11 through 15 due to this counter-flow heat exchanger effect.

The temperature difference between inlet and outlet of the module, showed a logarithmic decrease as the flow rate increased (Figure -27). A linear relationship was observed when the same graph was plotted on log-log scale (Figure -28 a and 28 b). These linear lines were observed to be parallel which helped in determining the correlation in terms of Stanton number and Reynolds number. The average surface temperature of the module showed the same trend of logarithmic decrease as the flow rate increased.

The heat dissipated by the coolant for all power settings was observed to be increasing as the flow rate increased (Figure 31). A tendency of higher heat dissipation level than the total power supplied to the heaters was observed. This arose in 33 of 63 experiments (50%) conducted for Side-A, with the highest increase of 10% (Power setting 2). Similar results were generated in the previous study and in the experiments conducted by the Crane Division of Naval Surface Warfare Center. This occurred in 60 of 80 runs (75%), during the previous study and 16 of 23 runs (69.6%) during the experiments conducted by NWSC [1,2]. According to the guidelines presented in the previous study related to the coolant specific heat, Delsen Laboratories data was used in calculations, in order to be able to acquire better results than before. However as mentioned earlier in 33 of 63 runs conducted for Side-A the same results as before were observed. 2.3% of the discrepancy in the heat dissipation level was explained by the uncertainty , calculated for q_{fluid}, in Appendix - B. However there still some amount of energy difference existed between the power into heaters and the heat dissipated by the coolant.

The general trend was observed as follows: The heat dissipation level was less than the total power supplied into the heaters at lower flow rates and it kept increasing as the flow rates increased. Thus the amount of heat dissipated by the coolant was more than the total power supplied by the heaters at high flow rates.

The criteria defined for steady state achievement, was assumed to be the same for higher flow rates. However some amount of fluctuations were observed at the inlet temperature of the coolant as the flow rate increased. This resulted in noticeable difference between the temperature differentials, even though steady state was assumed to be achieved. This might be the cause of higher heat dissipation levels observed at higher flow rates.

The general form of the correlations obtained by formulating the relationship between the Stanton and the Reynolds numbers was as follows:

$ln\,(\mathrm{St}) = \mathrm{m}^*\ ln\,(\mathrm{Re}) + \mathrm{n}$

or

$\mathrm{St} = \mathrm{A}^*\ \mathrm{Re}^{\mathrm{B}}$

The coefficient A, increases as the power increases and the maximum difference between the values of exponent B, is about 0.08 which is assumed to be in a reasonable range (Table 20). The increase in the coefficient A, can be explained by the Prandtl number effect of the coolant.

B. EXPERIMENTS CONDUCTED FOR SIDE-B

The decrease in the surface temperatures of the module was observed more clearly during the changes of the flow settings at lower flow rates as observed on Side-A. Cooling capability of the FTM was more significant during the first two flow settings which was the same result obtained from the first set of experiments. The same logarithmic trend, in the decrease of module surface temperatures was observed as the flow rate increased. The lowest and the highest temperatures consistently occurred at thermocouples 6 and 18 respectively. A sharp decrease in temperature was observed between thermocouples 5 and 6 which could be explained by the existence of the fins along this path.

The same trend of logarithmic decrease was observed in the average surface temperature vs. flow rate graph. Unlike Side-A, the heat dissipated by the coolant was always less than the total power supplied by the heaters.

The relationship between Reynolds and Stanton numbers was formulated in the same way as for Side - A. The coefficient A was also increasing as the power rate increased, which verified the Prandtl number effect of the coolant. The maximum difference in the values of the exponential B, is about 0.18.

VI. RECOMMENDATIONS

In order to be able to completely interpret the data obtained throughout this and the previous studies [1,2] knowledge of the internal configuration of the FTM would be required. This would also provide a valuable information in acquiring the correlation by making the corrections to the free-flow area. Unfortunately due to the proprietary nature of the FTM, it was not possible to cut it open.

The experiments can be repeated using water as the coolant of the system to compare the data and to determine the Prandtl number dependence on the effectiveness of the module.

The correlations in terms of Colburn j factor can be calculated using the data and the results can be compared with the ones obtained in a previous study [14].

The surface temperature patterns at various power and flow settings can be visualized by using thermochromic liquid crystals. The temperature data obtained in this and in the previous study can be compared with the pictures of these images [1].

APPENDIX A. SAMPLE CALCULATIONS

Sample calculations are based on power setting # 9 (100 Watts) of the first set of experiments for the flow rate of 350 ml/min. The results are tabulated in Table 13 and the procedure can be summarized as follows;

The current passing through each heater is calculated by using Equation 8 as:

$$I_h(i) = I_p(i) = \frac{V_p(i)}{R_p(i)} \tag{8}$$

where i is the index for heaters and precision resistors from 0 to 8. Thus for power setting #9 current passing through heater # 8 is calculated as;

$$I_h(8) = I_p(8) = \frac{V_p(8)}{R_p(8)}$$

$$I_p(8) = \frac{0.354}{0.5009} = 0.707A$$

and using Equation 9, the power supplied to the heater # 8 is calculated as:

$$P_h(8) = V_h(8) \times I_h(8) = 15.89 * 0.707 = 12.23 \text{ Watts.} \tag{9}$$

from Equation 11 heat flux generated by each heater is evaluated as:

$$q'' = \frac{1}{A_{eff}} \times \left(\frac{P_t}{9}\right) = 5.73 \text{ Watts / cm}^2 \tag{11}$$

where $\mathbf{A}_{\mathbf{eff}} = 1.94 \text{ cm}^2$

average of the differential between coolant inlet and outlet temperatures is calculated by using Equation 12 as follows:

$$\overline{T}_{diff} = \sum_{i=1}^{30} \frac{T_i(4) - T_i(3)}{30} = 10.21^oC \tag{12}$$

The thermophysical properties of the coolant, that is density and specific heat, are calculated by using Equation 1 and 3 respectively as follows:

$$\rho = -8.8216 \times 10^{-7} \times T_{avg}^2 - 7.9251 \times T_{avg} + 0.81055 = 0.7894 \quad \text{g/ml.} \tag{1}$$

$$c_p = (3.528 \times 10^{-4} \times T_{avg}^2 + 1.047 \times 10^{-3} \times T_{avg} + 0.4695) \times 4.184 \tag{3}$$

$$= 2.0791 \quad \text{J/g}\,^\circ\text{C}$$

$$\text{where} \quad T_{avg} = \frac{T_i(4) - T_i(3)}{2} = 25.92^oC \tag{2}$$

The volumetric flow rate, which is chosen to be 350 ml/min is calculated by using the following fourth order polynomial (Equation 5) obtained from the flowmeter calibrations:

$$\dot{Q} = 2.7178 \times 10^{-5}\alpha^4 - 6.02 \times 10^{-3}\alpha^3 + 0.4224\alpha^2 + 4.1837\alpha - 8.073 \quad \text{ml/min} \tag{5}$$

where is the flowmeter reading in percent, %. Therefore heat dissipated by the coolant can be calculated by using Equation 13 as follows:

$$q_{fluid} = \frac{\rho \dot{Q} c_p T_{avg}}{60} = 97.75 Watts \tag{13}$$

The average module surface temperature, which is utilized in heat loss calculation, is calculated by Equation 14 as follows:

$$\overline{T}_{surf} = \frac{\sum_{i=5}^{19} T(i)}{15} = 30.16^oC \tag{14}$$

The heat loss through the insulation is calculated by using Equation 15 as follows:

$$q_{loss} = \frac{kA}{L}\left[\overline{T}_{surf} - T(2)\right] \tag{15}$$

$$= \frac{0.04 \times 0.0219}{0.0191}(30.16 - 24.27) = 0.47 Watts$$

finally the difference in energy balance is calculated as;

$$\Delta q = P_t - q_{fluid} - q_{loss} = 100.025 - 97.75 - 0.47 = 1.805 Watts \tag{16}$$

The *Reynolds* and *Stanton* numbers are calculated by using Equations 18 and 19 respectively. Mean velocity of the fluid through the channels for the flow setting 350 ml/min is evaluated as follows:

$$U_m = \frac{\dot{Q}}{A_f} \tag{22}$$

$$= 350(\frac{ml}{\min})(\frac{1m^3}{10^6 ml})(\frac{1\min}{60\sec})\frac{1}{6.054 \times 10^{-5} m^2}$$

$$= 9.63 cm/s$$

The log mean temperature difference, used in Stanton number calculations is calculated for power setting # 9 as follows:

$$\Delta T_{LM} = \frac{\left(T(19) - \overline{T}_{out}\right) - \left(T(5) - \overline{T}_{in}\right)}{\ln\left[\left(T(19) - \overline{T}_{out}\right) \div \left(T(5) - \overline{T}_{in}\right)\right]} \tag{17}$$

$$= \frac{(34.4 - 31.03) - (23.47 - 20.82)}{\ln[(34.4 - 31.03) \div (23.47 - 20.82)]} = 2.996^o C$$

Using Equation 18, the Reynolds number is calculated as follows:

$$Re = \frac{U_m D_h}{\nu} = \frac{0.096 \times 1.323 \times 10^{-3}}{0.00005} = 2.54 \tag{18}$$

and finally, the Stanton number is evaluated by using Equation 19 as follows:

$$St = \frac{P_T}{\rho \dot{Q} c_p \Delta T_{LM}} = \frac{100.025}{0.7894 \times 2.0791 \times 350 \times 2.996} = 0.0581 \tag{19}$$

APPENDIX B. UNCERTAINTY ANALYSIS

There was some uncertainty in measurements taken during the experiments. These uncertainty values were either evaluated or estimated for all of the variables mentioned in sample calculations and summarized in Table 23.

The uncertainty of a function in the form, $f\,(x_1\,,x_2) = x_1 * x_2$ is evaluated by utilizing the following equation:

$$\delta_f = \left[\left(\frac{\delta x_1}{x_1} \right)^2 + \left(\frac{\delta x_2}{x_2} \right)^2 \right]^{1/2} \tag{23}$$

where;

x_1 and x_2	:	experimental variables.
δ_f	:	Total Uncertainty in Function f.
δ_{x_1}	:	Uncertainty in Variable x_1.
δ_{x_2}	:	Uncertainty in Variable x_2.

The uncertainty calculations were performed for power setting # 5 and flow setting of 950 ml/min. Where:

$\rho = 0.7929$ g/ml	$V_h = 12.288$ Volt	$V_p = 0.275$ Volt
$\nu = 6.3 \times 10^{-5} m^2/s$	$U_m = 0.262$ m/s	Re = 5.48
$c_p = 2.0607$ J/(g°C)	$\Delta T_{LM} = 1.332°C$	St = 0.0291
$\overline{T}_3 = 20.56°C$	$\overline{T}_4 = 23.00°C$	
$T_{avg} = 21.78$ °C	$R_p = 0.5009$ Ohm	

Therefore the uncertainty in power supplied to the heaters can be calculated using Equations 9 and 7:

$$P_h = V_h \times I_h \tag{9}$$

$$I_h = I_p = \frac{V_p}{R_p} \tag{7}$$

VARIABLE	UNIT	UNCERTAINTY	REFERENCE
R_P	Ohm	0.0001	Calibration of Precision Resistors
V_p & V_h	Volt	0.008 %+0.0007	Integrating Voltmeter Manual
I_P	Amp.	0.00263 %	Calculated Eqn.(24)
P_h	Watt	0.00263 %	Calculated Eqn.(25)
T	°C	0.12 °C	Thermocouple Calibration
T_{diff}	°C	0.078%	Calculated Eqn.(26)
ρ	g/ml	0.005	Estimated
c_p	J/g °C	0.005	Estimated
ν	m^2/s	10^{-6}	Estimated
α	%	1.5	Experimental Observations
$\dot{Q}$	ml/min	2.1%	Interpolation
A	m^2	10 %(0.00219 m^2)	Estimated
L	m	0.003m	Ruler Resolution
$\overline{T}_{surf}$	°C	0.078 %	Calculated Eqn.(26)
ΔT_{LM}	°C	1.52 %	Calculated Eqn.(36)
h	m	10^{-5}	Estimated
b	m	10^{-5}	Estimated
n	--	2.94 %	Estimated
A_c	m^2	1.08 %	Calculated Eqn.(30)
A_f	m^2	3.13 %	Calculated Eqn.(33)
D_h	m	1.53 %	Calculated Eqn.(29)
U_m	m/s	3.77 %	Calculated Eqn.(35)
q_{loss}	Watt	23.3 %	Calculated Eqn.(28)
q_{fluid}	Watt	2.34 %	Calculated Eqn.(27)
Re	--	4.37 %	Calculated Eqn.(37)
St	--	3.6 %	Calculated Eqn.(38)

Table 23. Uncertainty Values of the Variables

$$\frac{\delta_{I_p}}{I_p} = \sqrt{(\frac{\delta V_p}{V_p})^2 + (-\frac{\delta R_p}{R_p})^2} = 2.63 \times 10^{-3} \tag{24}$$

$$\frac{\delta_{P_h}}{P_h} = \sqrt{\left(\frac{\delta V_h}{V_h}\right)^2 + \left(\frac{\delta I_h}{I_h}\right)^2} = 0.00263 \tag{25}$$

$$\delta_{P_h} = \pm 0.158W$$

The uncertainty in average temperature differential from Equation 12:

$$T_{diff} = \bar{T}_4 - \bar{T}_3$$

$$\frac{\delta_{T_{diff}}}{T_{diff}} = \sqrt{(\frac{\delta \bar{T}_4}{\bar{T}_4})^2 + (\frac{\delta \bar{T}_3}{\bar{T}_3})^2} = 0.78 \tag{26}$$

$$\delta T_{diff} = \pm 0.0186^oC$$

The uncertainty in heat dissipation satisfied by the coolant is evaluated from Equation 13 by utilizing the above results as follows:

$$\frac{\delta q_{fluid}}{q_{fluid}} = \sqrt{(\frac{\delta q}{\rho})^2 + (\frac{\delta \dot{Q}}{\dot{Q}})^2 + (\frac{\delta c_p}{c_p})^2 + (\frac{\delta T_{diff}}{T_{diff}})^2} = 2.34\% \tag{27}$$

$$\delta_{q_{fluid}} = \pm 1.4W$$

The uncertainty in the flowmeter reading was ±1.5% with respect to the experimental observations. Therefore the uncertainty for this flow setting (950 ml/min) is calculated simply by interpolating according to the flowmeter calibration, and found to be 2.1%.

The uncertainty in heat losses through the insulation is calculated as follows:

$$\frac{\delta q_{loss}}{q_{loss}} = \sqrt{(\frac{\delta A}{A})^2 + (\frac{\delta \Delta T_{LOSS}}{\Delta T_{LOSS}})^2 + (\frac{\delta L}{L})^2} = 23.3\% \tag{28}$$

$\delta q_{loss} = \pm 0.009W$

The uncertainty calculations based on Reynolds and Stanton numbers are evaluated by calculating the uncertainties in the following parameters as follows:

The uncertainty in hydraulic diameter:

$$\frac{\delta D_h}{D_h} = \sqrt{(\frac{\delta A_c}{A_c})^2 + (-\frac{\delta P}{P})^2} \tag{29}$$

where;

$$\frac{\delta A_c}{A_c} \equiv \frac{\delta P}{P} = \sqrt{(\frac{\delta h}{h})^2 + (\frac{\delta b}{b})^2} = 0.0108 \tag{30}$$

since $A_c = h*b$ (31)

and $P = 2 * (h + b)$ (32)

Therefore the uncertainty in hydraulic diameter is;

$$\frac{\delta D_h}{D_h} = \sqrt{(0.0108)^2 + (0.0108)^2} = 0.0153$$

The uncertainty in free-flow area is evaluated as follows;

$$\frac{\delta A_f}{A_f} = \sqrt{(\frac{\delta h}{h})^2 + (\frac{\delta b}{b})^2 + (\frac{\delta n}{n})^2} = 0.0313 \tag{33}$$

where $A_f = h*b*n$ (34)

By using the result obtained from Equation (34), the uncertainty in the mean velocity of the coolant through the channels is calculated as follows:

$$\frac{\delta U_m}{U_m} = \sqrt{(\frac{\delta \dot{Q}}{\dot{Q}})^2 + (-\frac{\delta A_f}{A_f})^2} \tag{35}$$

$$= \sqrt{(0.021)^2 + (0.0313)^2} = 0.0377$$

where $$U_m = \frac{\dot{Q}}{A_f} \tag{22}$$

Finally, the uncertainty in the log-mean temperature difference is evaluated as follows:

$$\frac{\delta(\Delta T_{LM})}{\Delta T_{LM}} = \sqrt{2(\frac{\delta T_{19}}{T_{19}})^2 + 2(\frac{\delta \overline{T}_{out}}{\overline{T}_{out}})^2 + 2(\frac{\delta T_5}{T_5})^2 + 2(\frac{\delta \overline{T}_{in}}{\overline{T}_{in}})^2} \tag{36}$$

$$= \sqrt{2(\frac{0.12}{24.97})^2 + 2(\frac{0.12}{23})^2 + 2(\frac{0.12}{21.41})^2 + 2(\frac{0.12}{20.56})^2} = 0.0152$$

The above results can be utilized to calculate the uncertainties in the Reynolds and the Stanton numbers as follows:

$$\frac{\delta Re}{Re} = \sqrt{(\frac{\delta U_m}{U_m})^2 + (\frac{\delta D_h}{D_h})^2 + (-\frac{\delta \nu}{\nu})^2} = 0.0437 \tag{37}$$

$$\frac{\delta St}{St} = \sqrt{(\frac{\delta P_T}{P_T})^2 + (-\frac{\delta \rho}{\rho})^2 + (-\frac{\delta \dot{Q}}{\dot{Q}})^2 + (-\frac{\delta c_p}{c_p})^2 + [-\frac{\delta(\Delta T_{LM})}{\Delta T_{LM}}]^2} \tag{38}$$

$$= 0.0358$$

where $\frac{\delta P_T}{P_T} = 9 \times 0.02367 = 0.0213$ is the uncertainty in total power.

APPENDIX C. THERMOPHYSICAL PROPERTIES OF BRAYCO MICRONIC 889

The properties of the coolant, Brayco Micronic 889, are tabulated according to the data provided by the manufacturer, Castrol [3], as follows:

TEST (ASTM)	DESCRIPTION	RESULT
D-287	Specific Gravity	0.08
D-445	Kinematic Viscosity, (10^6 m^2/s)	
	@ 100 ^{0}C	1.7
	@ 40 ^{0}C	5.2
	@ - 40 ^{0}C	260
	@ - 54 ^{0}C	1,200
D-877	Dielectric Strength, (KV)	35
D-1169	Resistivity, 25^0 C (77 ^{0}F), (ohm-cm)	1.5-10^{10}
D-287	Density, (g / ml)	
	@ 0 ^{0}C (32 ^{0}F)	0.811
	@ 20 ^{0}C (68 ^{0}F)	0.794
	@ 40 ^{0}C (104 ^{0}F)	0.777
	@ 100 ^{0}C (212 ^{0}F)	0.723
	@ 160 ^{0} C (320 ^{0}F)	0.661
D-2766	Specific Heat (cal / g ^{0}C)	
	@ -18 ^{0}C (0 ^{0}F)	0.49
	@ 10 ^{0}C (50 ^{0} F)	0.52
	@ 38 ^{c}C (100 ^{0}F)	0.54
	@ 93 ^{0}C (200 ^{0}F)	0.58

D-1903	Coefficient of Thermal Expansion,	per ^{0} C
	0-50 ^{0} C	$8.3.10^{-4}$
	5-100 ^{0} C	$9.2.10^{-4}$
	100-150 ^{0} C	$10.3.10^{-4}$
	150-190 ^{0} C	$11.7.10^{-4}$
D-3114	Thermal Conductivity, BTU/hrft^2 (^{o} F/ft)	
	^{0} C ^{0} F	
	0 0	0.085
	10 50	0.083
	24 75	0.082
	38 100	0.082
	93 200	0.078
	149 300	0.075
	204 400	0.072
	260 500	0.069

Table 24. Properties of Brayco Micronic 889 [3].

APPENDIX D. QBASIC PROGRAM CODE

This Program was written in order to establish an interface between HP 3852A Data Acquisition / Control Unit and the Personal Computer. The program code is in QBASIC and it is located under the program group, "Thesis Items" in the PC. After operating the HP3852A, the program can be run by pressing F5 or by choosing "Run" from "File" menu while the file named "FTM.BAS" is open. Temperature and Voltage values acquired by HP 3852A are utilized throughout other calculations.

```
CLS
COLOR 14, 9
PRINT " Program for National Instruments PC2 IEEE-488 BOARD to HP-3852"
PRINT " This uses the Universal Language Interface"
PRINT " ULI.COM must be run prior to running the program"
PRINT " The  name of the program is  FTM.BAS"
        '****************************************
    'Preparing the interface between program and PC2 board.
OPEN "GPIB0" FOR OUTPUT AS #1
OPEN "GPIB0" FOR INPUT AS #2
    'Initializing the bus and reset to default parameters.
PRINT #1, "ABORT"
PRINT #1, "RESET"
        '****************************************
PRINT #1, "GPIBEOS CR LF"            'Establish end of string character.
PRINT #1, "CLEAR 9"                   'Clear device 9 which is HP-3852 .
STARTIT:
PRINT #1, "REMOTE 9"                  'Place it into Remote mode to accept
commands.
PRINT #1, "OUTPUT 9; RESET 700"      'Reset voltmeter in slot 7.
PRINT #1, "OUTPUT 9; USE 700"         'Use voltmeter in slot 7.
PRINT #1, "OUTPUT 9; CONF TEMPT"  'Configure for temperature, type  T. '
    ************* BEGIN TO TAKE DATA*****************
DIM TEMP(20), V(18), R(9), P(9)          'Defining dimensions for variables.
```

```
INPUT "ENTER FLOWRATE IN mL/min >", Flow
FOR I = 0 TO 19                          'For/Next Loop for channels; All 20
channels of
                                         ' the HP 44708A relay multiplexer.
CHNL$ = STR$(I + 300)
MSG$ = "OUTPUT 9;MEAS TEMPT" + CHNL$
                                               'Command to measure temperature
on channel I.

PRINT #1, MSG$                           ' Sending MEASURE command to HP-3852.
PRINT #1, "ENTER 9"                            'Call enter routine on interface
board.
INPUT #2, TMP$
TEMP(I) = VAL(TMP$)                      'Data returning into TMP$.
PRINT "THERMOCOUPLE "; (I); " = "; TEMP(I)
NEXT I
I = 0
PRINT #1, "OUTPUT 9;CONF DCV"            'Configuring for  DC Volt measurements.
PRINT #1, "OUTPUT 9;USE 700"


FOR I = 0 TO 17                                ' 18 channels are used for Heaters
and
                                                ' Precision Resistors.

CH$ = STR$(I + 200)                            ' Slot number for DCV measurements
is 2.
MESS$ = "OUTPUT 9;MEAS DCV" + CH$              'Measuring voltages on channels
200+I.
PRINT #1, MESS$
PRINT #1, "ENTER 9"                             'Calling ENTER routine.
INPUT #2, VOLT$
V(I) = VAL(VOLT$)                              'Data is stored to V(I).
NEXT I
```

```
PRINT #1, "OUTPUT 9;BEEP"
PRINT #1, "CLEAR 9"
PRINT #1, "LOCAL 9"
                                        'Precision  Resistors in Ohms.
R(0) = .4876
R(1) = .4877
R(2) = .4877
R(3) = .4878
R(4) = .4876
R(5) = .4876
R(6) = .5008
R(7) = .5
R(8) = .5009
TMPT = 0!                          'Calculating the module average surface
temperature.
I = 5
DO WHILE I < 20
I = I + 1
TMPT = TMPT + TEMP(I)
LOOP
TSURF = TMPT / 15                       ' Module average surface temperature.
PRINT "AVG SURF. TEMP";
PRINT USING "##.##"; TSURF
FOR I = 0 TO 8                     ' Printing Voltages and Total Power to screen.
P(I) = V(I) * (V(I + 9)) / R(I)    ' Calculating Power supplied by each Heater.
PRINT I;
PRINT USING "##.###"; V(I);        ' Voltage Drop across the Heaters.
PRINT USING "##.### "; V(I + 9);   ' Voltage Drop across the Precision Resistors.
PRINT USING "##.###"; P(I)
NEXT I
I = 0
TOTPWR = 0!
DO WHILE I < 10                    'Loop for Total Power calculation.
I = I + 1
```

```
TOTPWR = TOTPWR + P(I - 1)
LOOP
PRINT "TOTAL POWER INPUT =";
PRINT USING "##.###"; TOTPWR          'Total Power(Watts).
NEXT I
I = 0
T3 = 0!
PRINT TIME$;                          'Printing the time to screen.
DO WHILE I < 31             'Loop for calculating the average of 30 measurements
taken for                             ' coolant inlet and outlet temperatures.
I = I + 1
CHNL$ = STR$(303)
MSG$ = "OUTPUT 9;MEAS TEMPT" + CHNL$
PRINT #1, MSG$
PRINT #1, "ENTER 9"
INPUT #2, TMP$
T(1) = VAL(TEMP$)
T3 = T3 + T(I)
TIN = T3 / 30               ' Average value for the coolant inlet temperature.
LOOP
NEXT I
I = 0
T4 = 0!
PRINT TIME$;
DO WHILE I < 31
I = I + 1
CHNL$ = STR$(304)
MSG$ = "OUTPUT 9;MEAS TEMPT" + CHNL$
PRINT #1, MSG$
PRINT #1, "ENTER 9"
INPUT #2, TMP$
T(1) = VAL(TEMP$)
T4 = T4 + T(I)
TOUT = T4 / 30              ' Average value for the coolant outlet temperature.
```

```
LOOP
DIFF = TOUT - TIN            ' Difference between inlet and outlet temperatures.
TAVG = (TIN + TOUT) / 2  ' Average of inlet and outlet temperatures.
PRINT "Tin =";
PRINT USING "##.##"; TIN;
PRINT "Tout =";
PRINT USING "##.##"; TOUT;
NEXT I
FOR I = 0 TO 4               'Printing temperatures to screen.
PRINT I;
PRINT USING "##.##"; TEMP(I);
PRINT I + 5;
PRINT USING "##.##"; TEMP(I + 5);
PRINT I + 10;
PRINT USING "##.##"; TEMP(I + 10);
PRINT I + 15;
PRINT USING "##.##"; TEMP(I + 15)
NEXT I
                             'Calculation for the heat transferred through the Insulation.
DTINS = TEMP(1) - TEMP(0)
K = .04                                'Conductivity of the insulator.
A = .0219                    'Surface area of the insulation Area.
L = .0191                    'Insulation Thickness.
QINS = K * A * DTINS / L
                             'Calculation for coolant thermophysical properties.
A1 = -8.8216E-07             'Coefficients of density curvefit.
B1 = -7.9251E-04
C1 = 8.1055
DENSITY = A1 * TAVG ^ 2 + B1 * TAVG + C1
A2 = 3.5284E-07                'Coefficients of specific heat curvefit .
B2 = .0010466
C2 = .46955
SPECHEAT = A2 * TAVG ^ 2 + B2 * TAVG + C2
QFLUID = DENSITY * SPECHEAT * Flow * DIFF / 60
```

```
QTOTAL = QFLUID + QINS
DELQ = QTOTAL - TOTPWR
PRINT "Qfluid=";
PRINT USING "##.## "; QFLUID;  'Heat absorbed by the fluid.
PRINT "Qins=";
PRINT USING "##.## "; QINS;
PRINT "Qtotal=";
PRINT USING "##.## "; QTOTAL;
PRINT "DelQ=";
PRINT USING "##.## "; DELQ
PRINT "dTins=";
PRINT USING "#.## "; DTINS;
PRINT "dTfluid=";
PRINT USING "##.##     "; DTFLU;
PRINT TIME$       ' PRINT #1, "OUTPUT 9;BEEP"       'Make HP-3852 Beep when
done
PRINT #1, "CLEAR 9"                                   'Clear and reset device 9.
PRINT #1, "LOCAL 9"
INPUT "  DO YOU WISH TO SAVE DATA ?  ", SAVIT$    'Decision to save the data
or not.
IF SAVIT$ = "n" THEN GOTO QUES
IF SAVIT$ = "N" THEN GOTO QUES

FILEIT:                               'Storing the data into a file
PRINT " IF A DATA FILE ALREADY EXISTS WITH THE NAME YOU SELECT, "
PRINT " PREVIOUS DATA WILL BE OVERWRITTEN  "
INPUT " ENTER THE NAME OF THE DATA FILE TO CREATE  ", FILE$
IF FILE$ = "" THEN GOTO FILEIT OPENIT:
OPEN FILE$ FOR OUTPUT AS #3
PRINT #3, "mL/min"                                'Flow rate , ml/min.
PRINT #3, Flow
PRINT #3, "Vhtr "                                 'Heater voltage drop, Volts.
FOR I = 0 TO 8
PRINT #3, USING "##.###"; V(I)
```

```
NEXT I
PRINT #3, "Vr"                                'Precision Resistor voltage drop,
Volts.
FOR I = 0 TO 8
PRINT #3, USING "##.###"; V(I + 9)
NEXT I
PRINT #3, "POWER"
FOR I = 0 TO 8
PRINT #3, USING "##.###"; P(I)                'Power supplied to each heater,
Watts.
NEXT I
PRINT #3, "TOT. POWER"
PRINT #3, USING "##.###"; TOTPWR              'Total Power, Watts.
PRINT #3, "AVG SURF. TEMP";
PRINT #3, USING "##.##"; TSURF                'Module average surface
temperature, ° C.
PRINT #3, "Tin ="
PRINT #3, USING "##.##"; TIN                  'Coolant inlet temperature, ° C.
PRINT #3, "Tout ="
PRINT #3, USING "##.##"; TOUT                 'Coolant outlet temperature, ° C.
PRINT #3, "Qfluid="
PRINT #3, USING "##.##"; QFLUID                       'Heat absorbed by the
coolant, Watts.
PRINT #3, "Qins="
PRINT #3, USING "##.##"; QINS                 'Heat loss through the insulation,
Watts.
PRINT #3, "Qtotal="
PRINT #3, USING "##.##"; QTOTAL               'Total heat, Watts.
PRINT #3, "DelQ="
PRINT #3, USING "##.##"; DELQ                 'Difference in energy balance, Watts.
PRINT #3, "dTins="
PRINT #3, USING "#.##"; DTINS                 'Temperature difference for the
insulation.
PRINT #3, "dTfluid="
```

```
PRINT #3, USING "##.##"; DTFLU                  'Temperature difference for the
coolant.
PRINT #3, "DEG C"
FOR I = 0 TO 19
PRINT #3, USING "##.##"; TEMP(I)                'Temperature readings, ° C.
PRINT #3, DATE$                                 'Printing the date.
PRINT #3, TIME$                                 'Printing the time.
CLOSE #3
QUES:                              'Questioning.
INPUT " DO YOU WISH TO TRY ANOTHER RUN ( Y/N )  ?  ", AGAIN$
IF AGAIN$ = "Y" THEN GOTO STARTIT
IF AGAIN$ = "y" THEN GOTO STARTIT
IF AGAIN$ = "N" THEN END
IF AGAIN$ = "n" THEN END
GOTO QUES
        END
```

APPENDIX E. MATLAB CODES OF CALIBRATION CALCULATIONS

The calibration calculations are performed by using Matlab codes as follows:

```
% FLOWMETER (FISCHER & PORTER) CALIBRATION CURVE
% 4th ORDER POLYNOMIAL
rate=[0 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100]; % FLOW
PERCENTAGE
flow=[0 62.67 125.38 182.58 280.31 370.37 449.44 534.19 597.01 671.59 742.12 802.25
    884.17 941.18 995.02 1052.63 1120.45 1208.46 1267.43 1314.06];%FLOW(ml/min)
f=polyfit(rate,flow,4);
% 4th ORDER POLYNOMIAL OF THE FLOWMETER CALIBRATION CURVE
rate1=[0:1:100];
f1=polyval(f,rate1);
plot(rate1,f1,rate,flow,'*'),grid; axis([-5 105 0 1500]);
title ('FLOWMETER CALIBRATION CURVE');
xlabel('FLOW PERCENTAGE'); ylabel('FLOW RATE (ml/min)');
gtext('16 MAY 1995');
f;      % COEFFICIENTS OF THE  POLYNOMIAL

% DENSITY CURVE OF THE COOLANT
% BRAYCO MICRONIC 889
% MANUFACTURER'S DATA
temp=[0 20 40 100 160];           % DEGREES CELSIUS
dens=[.811 .794 .777 .723 .661];  % DENSITY g/ml
f=polyfit(temp,dens,2);           % 2nd ORDER POLYNOMIAL OF THE DENSITY
CURVE temp1=[0:1.0:160];
f1=polyval(f,temp1);
plot(temp1,f1,temp,dens,'*'),grid;
axis([-5 180 0.64 0.82]);
title ('DENSITY CURVE of the COOLANT (BRAYCO MICRONIC 889)');
xlabel('TEMPERATURE (Deg. Celsius)');   ylabel('DENSITY (g/ml)');
f;      % COEFFICIENTS  OF THE  POLYNOMIAL
```

```
% SPECIFIC HEAT vs TEMPERATURE CURVE OF THE COOLANT
% BRAYCO MICRONIC 889
%  DELSEN LAB'S DATA
temp=[10 38 66 93];      % DEGREES CELSIUS
heat=[.48 .51 .54 .57];  % SPECIFIC HEAT cal/g-C
f=polyfit(temp,heat,2);            % 2nd ORDER POLYNOMIAL OF THE DENSITY
CURVE temp1=[-20:1.0:100];
f1=polyval(f,temp1);
plot(temp1,f1,temp,heat,'*'),grid;
axis([0 100 0.46 0.58]);
title ('SPECIFIC HEAT CURVE');
xlabel('TEMPERATURE (Deg. Celsius)'); ylabel('SPECIFIC HEAT (cal/g-C)');
f;        % COEFFICIENTS OF THE  POLYNOMIAL
```

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